Pilot Guide to Airplane Upset Recovery
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2.0 Introduction

The "Pilot Guide to Airplane Upset Recovery" is one part of the *Airplane Upset Recovery Training Aid*. The other parts include an "Overview for Management" (Sec. 1), "Example Airplane Upset Recovery Training Program" (Sec. 3), "References for Additional Information" (Sec. 4), and a two-part video.

The goal of this training aid is to increase the ability of pilots to *recognize and avoid* situations that can lead to airplane upsets and to improve their ability to recover control of an airplane that has exceeded the normal flight regime. This will be accomplished by increasing awareness of potential upset situations and knowledge of aerodynamics and by application of this knowledge during simulator training scenarios.

The education material and the recommendations provided in the *Airplane Upset Recovery Training Aid* were developed through an extensive review process by a large industry group in order to achieve a consensus of the air transport industry.

Because of the infinite variables that comprise upset situations, the industry group unanimously agrees that airplane upset recovery education must not include simulator testing criteria. By definition, testing implies procedure demonstration and objective assessment of performance. The goal of upset recovery is to regain aircraft flight path control. A testing environment could lead to similar negative learning conclusions that can currently exist with approach to stall performance when measured against minimum loss of altitude.

2.1 Objectives

The objectives of the "Pilot Guide to Airplane Upset Recovery" are to provide pilots with

- Knowledge to recognize situations that may lead to airplane upsets so that they may be prevented.
- Basic airplane aerodynamic information.
- Airplane flight maneuvering information and techniques for recovering airplanes that have been upset.

It is intended that this information be provided to pilots during academic training and that it be retained for future use.

2.2 Definition of Airplane Upset

Research and discussions within the commercial aviation industry indicated that it was necessary to establish a descriptive term and definition in order to develop this training aid. Terms such as "unusual attitude," "advanced maneuver," "selected event," "loss of control," "airplane upset," and others are terms used within the industry. The team decided that "airplane upset" was appropriate for this training aid. It is important to be clear on two factors. First is the notion of *unintentional*. In other words, the aircraft is not doing what it was being commanded to do and is approaching unsafe parameters. Second is the fact that a pilot must not wait until the airplane is in a fully developed and definable upset before taking corrective action to return to stabilized flight path parameters. Therefore, in order to identify acceptable references that define a developed upset condition, the following values were agreed upon. An airplane upset is defined as an airplane in flight unintentionally exceeding the parameters normally experienced in line operations or training. In other words, the airplane is not doing what it was commanded to do and is approaching unsafe parameters.

While specific values may vary among airplane models, the following unintentional conditions generally describe an airplane upset:

- Pitch attitude greater than 25 deg, nose up.
- Pitch attitude greater than 10 deg, nose down.
- Bank angle greater than 45 deg.
- Within the above parameters, but flying at airspeeds inappropriate for the conditions.

It should be emphasized that recovery to a stabilized flight path *should* be initiated as soon as a developing upset condition is recognized. The amount and rate of control input to counter a developing upset must be *proportional* to the *amount and rate of pitch, roll and/or yaw experienced.* This preventive action may alleviate what might have become a more serious event.

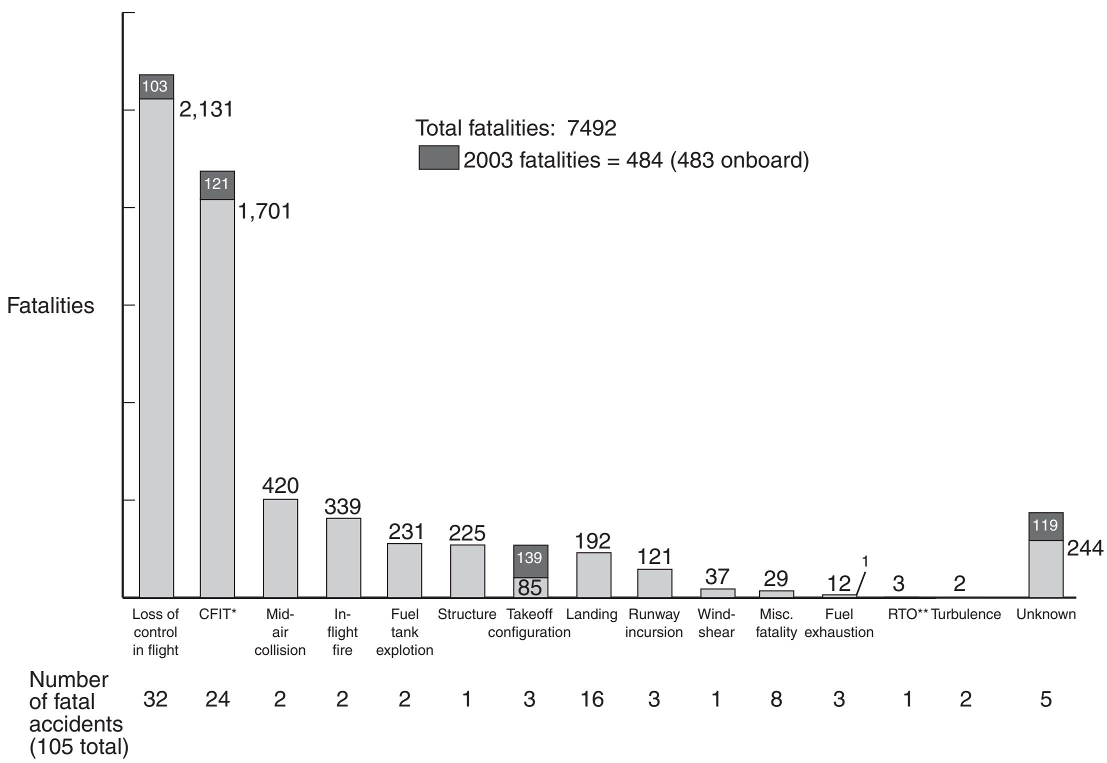
2.3 The Situation

The commercial aviation industry has not specifically tracked airplane upset incidents that meet this training aid's precise definition; therefore, safety data do not directly correlate to the upset parameters established for this training aid. However, the data that are available suggest that loss of control is a problem that deserves attention. Figure 1 shows that loss of control in flight accounted for many fatalities during the indicated time period.

2.4 Causes of Airplane Upsets

Airplane upsets are not a common occurrence. This may be for a variety of reasons. Airplane design and certification methods have improved. Equipment has become more reliable. Perhaps training programs have been effective in teaching pilots to avoid situations that lead to airplane upsets. While airplane upsets seldom take place, there are a variety of reasons why they happen. Figure 2 shows incidents and causes from NASA Aviation Safety Reporting System (ASRS) reports. The National Transportation Safety Board analysis of 20 transport-category loss-of-control accidents from 1986 to 1996 indicates that the majority were caused by the airplane stalling (Fig. 3). This section provides a review of the most prevalent causes for airplane upsets.

Figure 1
Worldwide Commercial Jet Fleet Fatalities Classified by Type of Event, 1994 to 2003



* CFIT = Controlled Flight Into Terrain
** RTO = Refused Takeoff

Note: Accidents involving multiple, non-onboard fatalities are included. Accidents involving single. non-onboard fatalities are excluded. Fatalities/accidents are placed in one category only.

2.4.1 Environmentally Induced Airplane Upsets

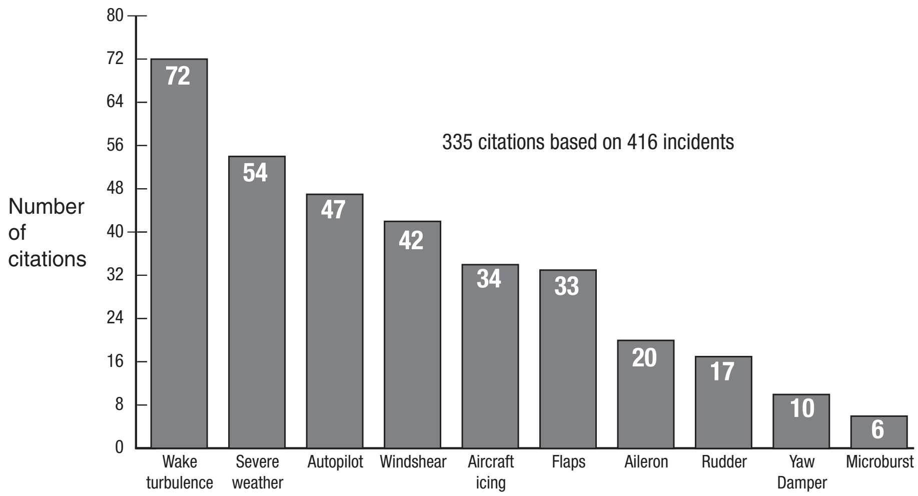
The predominant number of airplane upsets are caused by various environmental factors (Fig. 2). Unfortunately, the aviation industry has the least amount of influence over the environment when compared to human factors or airplane-anomaly-caused upsets. The industry recognizes this dilemma and resorts to training as a means for avoiding environmental hazards. Separate education and training aids have been produced through an industry team process that addresses turbulence, windshear, and wake turbulence.

Avoidance of environmentally induced upsets is the best course of action. Pilots should montor the environmental conditions and avoid high risk situations.

2.4.1.1 Turbulence

"Turbulence, when extreme, can lead to airplane upsets, and/or structural damage. These incidents of turbulence can cause large airspeed, altitude, or attitude deviations. The aircraft may be momentarily out of control. Severe or extreme turbulence can be associated with CAT (Clear Air Turbulence), mountain waves, windshear, thunderstorms, and wake turbulence."[2]

Turbulent atmosphere is characterized by a large variation in an air current over a short distance. The main causes of turbulence are jet streams, convective currents, obstructions to wind flow, and windshear. Turbulence is categorized as "light," "moderate," "severe," and "extreme." Refer to an industry-produced *Turbulence Education and Training Aid* for more information about turbu-



- Data references ASRS reports that have received full-form analysis and include the reporters' narrative.
- Categories are not mutually exclusive; therefore, a single incident may be coded by ASRS analysts as involving more than one citation. As an example, a pilot may experrience severe weather, wake turbulence, and icing in the same incident.
- Data are based on inflight loss of aircraft control reports containing any reference to those categories in the reporters' narratives.

Figure 2 Multiengine Turbojet Loss-of-Control Incidents, January 1996 to August 2002, ASRS

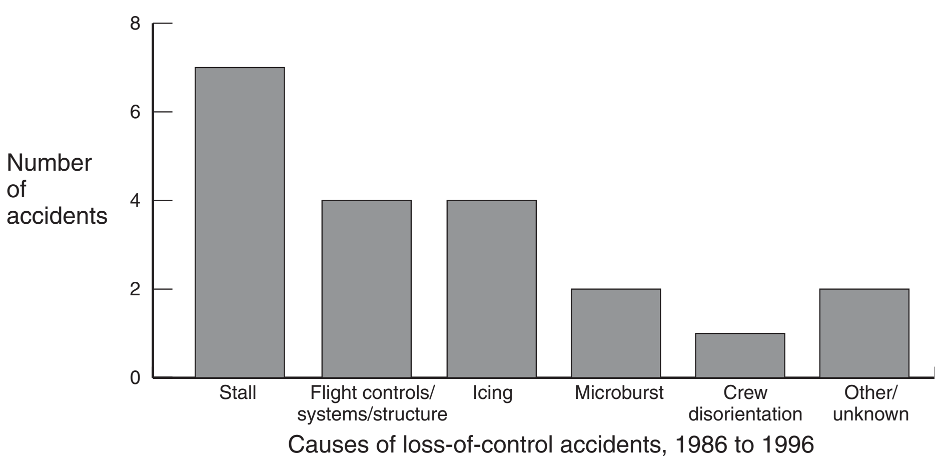


Figure 3 Loss-of-Control Accidents (Transport Category)

2. Source: *Turbulence Education and Training Aid*, U.S. Department of Transportation, Federal Aviation Administration, Air Transport Association of America, The Boeing Company, National Technical Information Services (Seattle, Washington, USA: May 1997).

lence. This aid is available from the National Technical Information Service or The Boeing Company. Only limited information is presented in this section for a short review of the subject. Knowledge of the various types of turbulence assists in avoiding it and, therefore, the potential for an airplane upset.

In one extreme incident, an airplane encountered severe turbulence that caused the number 2 engine to depart the airplane. The airplane entered a roll 50 deg left, followed by a huge yaw. Several pitch and roll oscillations were reported. The crew recovered and landed the airplane.

2.4.1.1.1 Clear Air Turbulence

Clear air turbulence (CAT) is defined by the Aeronautical Information Manual as "high-level turbulence (normally above 15,000 ft above sea level) not associated with cumuliform cloudiness, including thunderstorms."

Although CAT can be encountered in any layer of the atmosphere, it is almost always present in the vicinity of jet streams. A number of jet streams (high-altitude paths of winds exceeding velocities of 75 to 100 kn) may exist at any given time, and their locations will vary constantly. CAT becomes particularly difficult to predict as it is extremely dynamic and does not have common dimensions of area or time. In general, areas of turbulence associated with a jet stream are from 100 to 300 mi long, elongated in the direction of the wind; 50 to 100 mi wide; and 2000 to 5000 ft deep. These areas may persist from 30 min to 1 day. CAT near the jet stream is the result of the difference in windspeeds and the windshear generated between points. CAT is considered moderate when the vertical windshear is 5 kn per 1000 ft or greater and the horizontal shear is 20 kn per 150 nm, or both. Severe CAT occurs when the vertical shear is 6 kn per 1000 ft and the horizontal shear is 40 kn per 150 nm or greater, or both.

2.4.1.1.2 Mountain Wave

Mountains are the greatest obstructions to wind flow. This type of turbulence is classified as "mechanical" because it is caused by a mechanical disruption of wind. Over mountains, rotor or lenticular clouds are sure signs of turbulence. However, mechanical turbulence may also be present in air too dry to produce clouds. Light to extreme turbulence is created by mountains.

Severe turbulence is defined as that which causes large, abrupt changes in altitude or attitude. It usually causes large variation in indicated airspeed. The airplane may be momentarily out of control. Severe turbulence can be expected in mountainous areas where wind components exceeding 50 kn are perpendicular to and near the ridge level; in and near developing and mature thunderstorms; occasionally, in other towering cumuliform clouds; within 50 to 100 mi on the cold side of the center of the jet stream; in troughs aloft; and in lows aloft where vertical windshears exceed 10 kn per 1000 ft and horizontal windshears exceed 40 kn per 150 nm.

Extreme turbulence is defined as that in which the airplane is violently tossed around and practically impossible to control. It may cause structural damage. Extreme turbulence can be found in mountain-wave situations, in and below the level of well-developed rotor clouds, and in severe thunderstorms.

2.4.1.1.3 Windshear

Wind variations at low altitude have long been recognized as a serious hazard to airplanes during takeoff and approach. These wind variations can result from a large variety of meteorological conditions, such as topographical conditions, temperature inversions, sea breezes, frontal systems, strong surface winds, and the most violent forms of wind change—thunderstorms and rain showers. Thunderstorms and rain showers may produce an airplane upset, and they will be discussed in the following section. The *Windshear Training Aid* provides comprehensive information on windshear avoidance and training. This aid is available from the National Technical Information Service or The Boeing Company.

2.4.1.1.4 Thunderstorms

There are two basic types of thunderstorms: airmass and frontal. Airmass thunderstorms appear to be randomly distributed in unstable air, and they develop from localized heating at the Earth's surface (Fig. 4). The heated air rises and cools to form cumulus clouds. As the cumulus stage continues to develop, precipitation forms in high portions of the cloud and falls. Precipitation signals the beginning of the mature stage and the presence of a downdraft.

After approximately an hour, the heated updraft creating the thunderstorm is cut off by rainfall. Heat is removed and the thunderstorm dissipates. Many thunderstorms produce an associated cold-air gust front as a result of the downflow and outrush of rain-cooled air. These gust fronts are usually very turbulent, and they can create a serious airplane upset, especially during takeoff and approach.

Frontal thunderstorms are usually associated with weather systems line fronts, converging wind, and troughs aloft (Fig. 5). Frontal thunderstorms form in squall lines; last several hours; generate heavy rain, and possibly hail; and produce strong gusty winds, and possibly tornadoes. The principal distinction in formation of these more severe thunderstorms is the presence of large, horizontal wind changes (speed and direction) at different altitudes in the thunderstorm. This causes the severe thunderstorm to be vertically tilted. Precipitation falls away from the heated updraft, permitting a much longer storm development period. Resulting airflows within the storm accelerate to much higher vertical velocities, which ultimately results in higher horizontal wind velocities at the surface. The downward moving column of air, or downdraft, of a typical thunderstorm is fairly large, about 1 to 5 mi in diameter. Resultant outflows may produce large changes in windspeed.

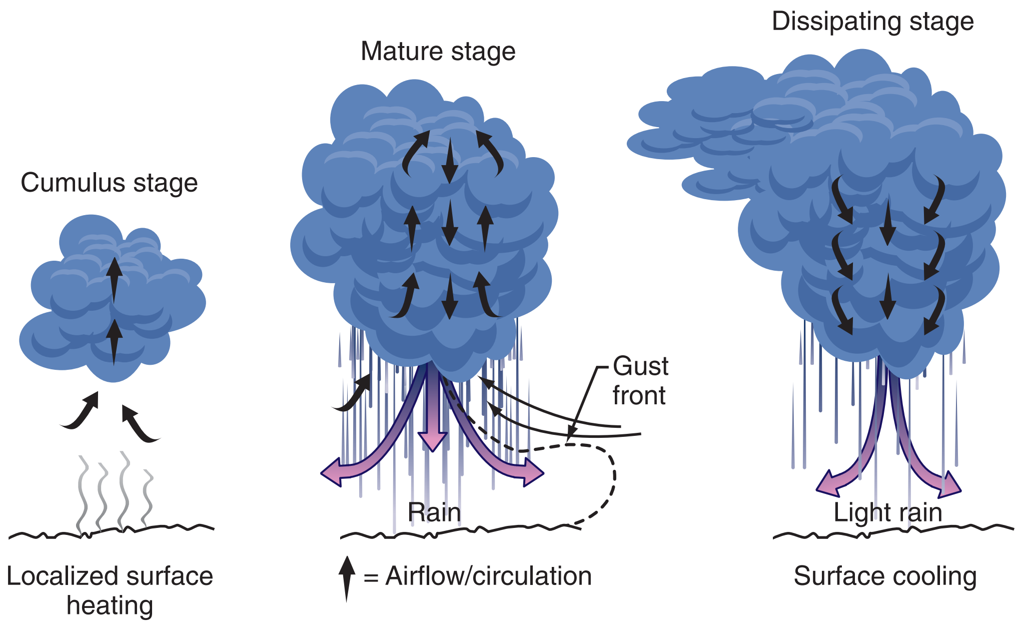


Figure 4
Airmass Thunderstorm Life Cycle

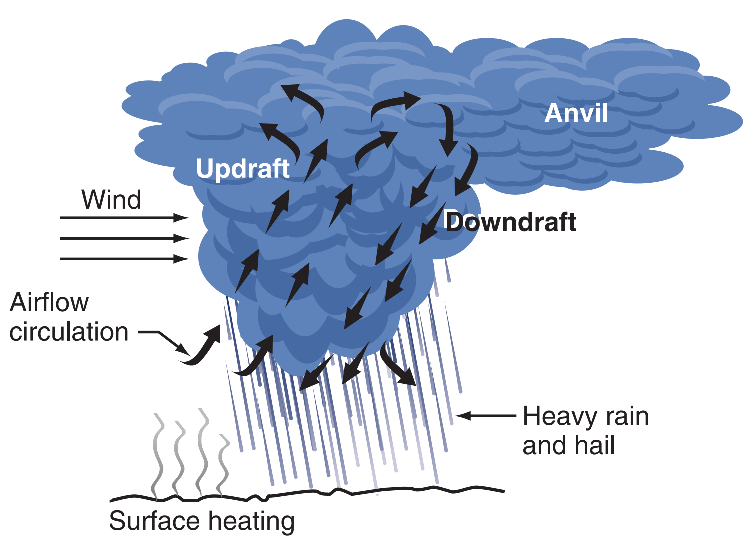


Figure 5
Severe Frontal Thunderstorm Anatomy

2.4.1.1.5 Microbursts

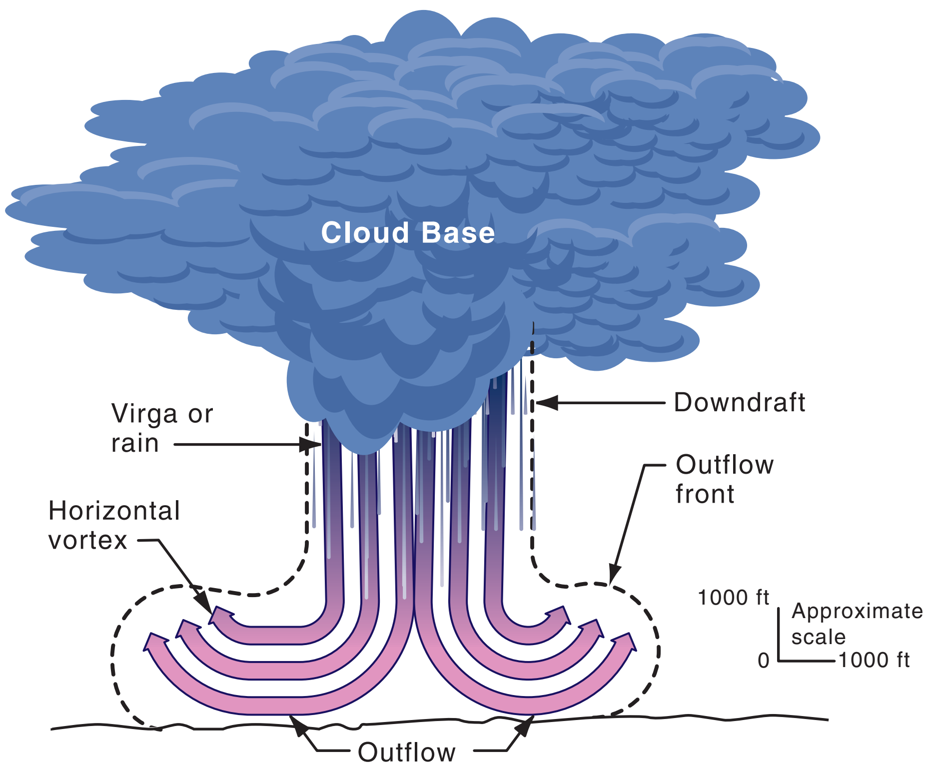
Identification of concentrated, more powerful downdrafts—known as microbursts—has resulted from the investigation of windshear accidents and from meteorological research. Microbursts can occur anywhere convective weather conditions occur. Observations suggest that approximately 5% of all thunderstorms produce a microburst. Downdrafts associated with microbursts are typically only a few hundred to 3000 ft across. When a downdraft reaches the ground, it spreads out horizontally and may form one or more horizontal vortex rings around the downdraft (Fig. 6). Microburst outflows are not always symmetric. Therefore, a significant airspeed increase may not occur upon entering outflows, or it may be much less than the subsequent airspeed loss experienced when exiting the microburst. Windspeeds intensify for about 5 min after a microburst initially contacts the ground and typically dissipate within 10 to 20 min after ground contact.

It is vital to recognize that some microbursts cannot be successfully escaped with any known techniques.

2.4.1.2 Wake Turbulence

Wake turbulence is the leading cause of airplane upsets that are induced by the environment. However, a wake turbulence penetration does not necessarily mean an airplane will become upset. The phenomenon that creates wake turbulence results from the forces that lift the airplane. High-pressure air from the lower surface of the wings flows around the wingtips to the lower pressure region above the wings. A pair of counterrotating vortices are thus shed from the wings: the right

Figure 6 Symmetric Microburst—An airplane transiting the microburst would experience equal headwinds and tailwinds.



wing vortex rotates counterclockwise, and the left wing vortex rotates clockwise (Fig. 7). The region of rotating air behind the airplane is where wake turbulence occurs. The strength of the turbulence is determined predominantly by the weight, wingspan, and speed of the airplane. Generally, vortices descend at an initial rate of about 300 to 500 ft/min for about 30 sec. The descent rate decreases and eventually approaches zero at between 500 and 900 ft below the flight path. Flying at or above the flight path provides the best method for avoidance. Maintaining a vertical separation of at least 1000 ft when crossing below the preceding aircraft may be considered safe. This vertical motion is illustrated in Figure 8. Refer to the *Wake Turbulence Training Aid* for comprehensive information on how to avoid wake turbulence. This aid is available from the National Technical Information Service or The Boeing Company.

An encounter with wake turbulence usually results in induced rolling or pitch moments; however, in rare instances an encounter could cause structural damage to the airplane. In more than one instance, pilots have described an encounter to be like "hitting a wall." The dynamic forces of the vortex can exceed the roll or pitch capability of the airplane to overcome these forces. During test programs, the wake was approached from all directions to evaluate the effect of encounter direction on response. One item was common to all encounters: with little to no control input from the pilot, the airplane would be expelled from the wake and an airplane upset could result.

Opposing the roll moment using normal roll control (aileron and roll spoiler) is usually effective and induced roll is minimal in cases where the wingspan and ailerons of the encountering air-

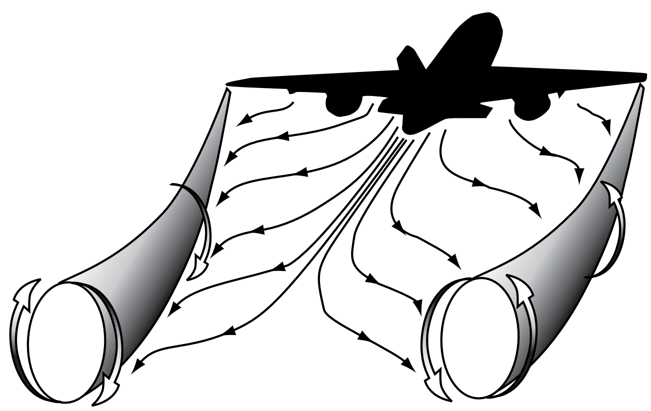


Figure 7
Wake Turbulence Formation

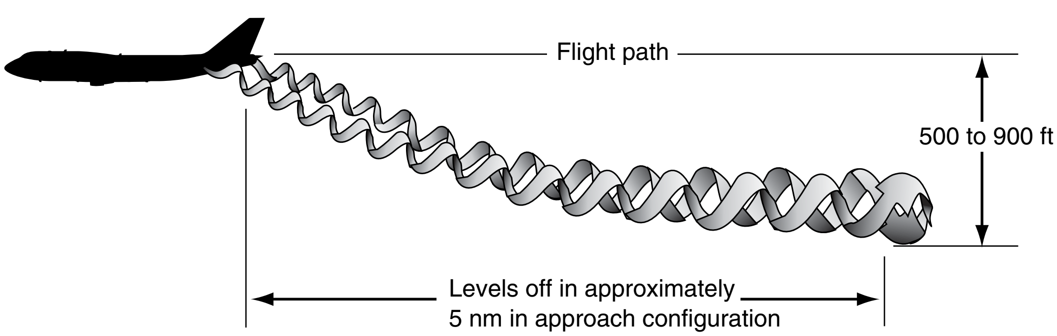


Figure 8
Vertical Motion Out of Ground Effect

plane extend beyond the rotational flowfield of the vortex (Fig. 9). It is more difficult for airplanes with short wingspan (relative to the generating airplane) to counter the imposed roll induced by the vortex flow.

Avoiding wake turbulence is the key to avoiding many airplane upsets. Pilot and air traffic control procedures and standards are designed to accomplish this goal, but as the aviation industry expands, the probability of an encounter also increases.

2.4.1.3 Airplane Icing

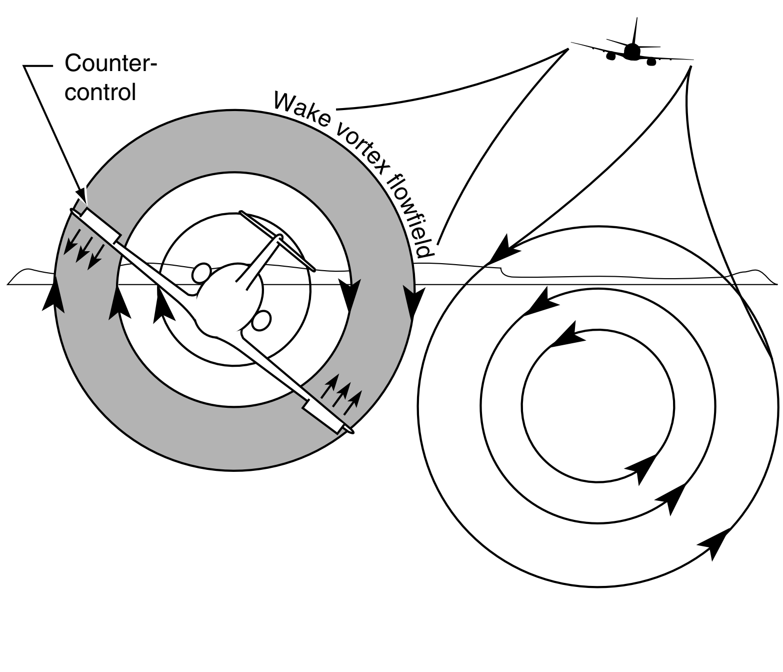
Technical literature is rich with data showing the adverse aerodynamic effects of airfoil contamination. Large degradation of airplane performance can result from the surface roughness of an extremely small amount of contamination. These detrimental effects vary with the location and roughness, and they produce unexpected airplane handling characteristics, including degradation of maximum lift capability, increased drag, and possibly unanticipated changes in stability and control. Therefore, the axiom of "keep it clean" for critical airplane surfaces continues to be a universal requirement.

2.4.2 Systems-Anomalies-Induced Airplane Upsets

Airplane designs, equipment reliability, and flight crew training have all improved since the Wright brothers' first powered flight. Airplane certification processes and oversight are rigorous. Airlines and manufacturers closely monitor equipment failure rates for possible redesign of airplane parts or modification of maintenance procedures. Dissemination of information is rapid if problems are detected. Improvement in airplane designs and equipment components has always been a major focus in the aviation industry. In spite of this continuing effort, there are still failures. Some of these failures can lead to an airplane upset. That is why flight crews are trained to overcome or mitigate the impact of the failures. Most failures are survivable if correct responses are made by the flight crew.

An airplane was approaching an airfield and appeared to break off to the right for a left downwind to the opposite runway. On downwind at approximately 1500 ft, the airplane pitched up to nearly 60 deg and climbed to an altitude of nearly 4500 ft, with the airspeed deteriorating to almost 0 kn. The airplane then tail-slid, pitched down, and seemingly recovered. However, it continued into an-

Figure 9
Induced Roll



other steep pitchup of 70 deg. This time as it tail-slid, it fell off toward the right wing. As it pitched down and descended again, seemingly recovering, the airplane impacted the ground in a flat pitch, slightly right wing down. The digital flight data recorder indicated that the stabilizer trim was more than 13 units nose up. The flight crew had discussed a trim problem during the descent but made no move to cut out the electric trim or to manually trim. The accident was survivable if the pilot had responded properly.

2.4.2.1 Flight Instruments

The importance of reliable flight instruments has been known from the time that pilots first began to rely on artificial horizons. This resulted in continual improvements in reliability, design, redundancy, and information provided to the pilots.

However, instrument failures do infrequently occur. All airplane operations manuals provide flight instrument system information so that when failures do happen, the pilot can analyze the impact and select the correct procedural alternatives. Airplanes are designed to make sure pilots have at least the minimum information needed to safely control the airplane.

In spite of this, several accidents point out that pilots are not always prepared to correctly analyze the alternatives, and an upset takes place. During the takeoff roll, a check of the airspeed at 80 kn revealed that the captain's airspeed was not functioning. The takeoff was continued. When the airplane reached 4700 ft, about 2 min into the flight, some advisory messages appeared informing the crew of flight control irregularities. Comments followed between the pilots about confusion that was occurring between the airspeed indication systems from the left-side airspeed indication system, affecting the indication of the left-side airspeed autopilot and activation of the overspeed warning. The airplane continued flying with the autopilot connected and receiving an erroneous indication in the captain's airspeed. Recorded sounds and flight data indicated extreme conditions of flight, one corresponding to overspeed and the other to slow speed (stick shaker). The captain initiated an action to correct the overspeed, and the copilot advised that his airspeed indicator was decreasing. The airplane had three airspeed indicating systems, and at no time did the flight crew mention a comparison among the three systems. The flight recorders indicated the airplane was out of control for almost 2 min until impact. Experts determined that the anomalies corresponded to conditions equal to an obstruction in the captain's airspeed sensors (pitot head).

2.4.2.2 Autoflight Systems

Autoflight systems include the autopilot, autothrottles, and all related systems that perform flight management and guidance. The systems integrate information from a variety of other airplane systems. They keep track of altitude, heading, airspeed, and flight path with unflagging accuracy. The pilot community has tended to develop a great deal of confidence in the systems, and that has led to complacency in some cases. As reliable as the autoflight systems may be, they can, and have, malfunctioned. Because of the integration of systems, it may even be difficult for the pilot to analyze the cause of the anomaly, and airplane upsets have occurred. Since advanced automation may tend to mask the cause of the anomaly, an important action in taking control of the airplane is to reduce the level of automation. Disengaging the autopilot, the autothrottles, or both, may help in analyzing the cause of the anomaly by putting the pilot in closer touch with the airplane and perhaps the anomaly.

2.4.2.3 Flight Control and Other Anomalies

Flight control anomalies, such as flap asymmetry, spoiler problems, and others, are addressed in airplane operations manuals. While they are rare events, airplane certification requirements ensure that pilots have sufficient information and are trained to handle these events. However, pilots should be prepared for the unexpected, especially during takeoffs. Engine failure at low altitudes while the airplane is at a low-energy condition is still a demanding maneuver for the pilot to handle. An erroneous stall warning on takeoff or shortly after takeoff could be a situation that allows the airplane to become upset.

A stall warning during takeoff could be the result of an incorrect V speed, incorrect flap or stabilizer position, a malfunctioning stall warning system, or a shift in cg during rotation. If an aircraft rotates at the wrong speed or in the wrong configuration, or when a malfunctioning stall warning system activates, care must be taken to adjust the flight profile so that airspeed and altitude will increase. Remember that if the airplane flies too slow, induced drag will increase and it may be necessary to reduce the

pitch attitude in order to accelerate. If a shift of cargo occurs, it may be helpful to leave the flaps and slats extended until approaching the limit speeds, where the horizontal tail has more pitch authority. For more information on the subject, refer to Section 2.6.3.2, "Nose-High, Wings-Level Recovery Techniques."

2.4.3 Pilot-Induced Airplane Upsets

We have known for many years that sensory inputs can be misleading to pilots, especially when they cannot see the horizon. To solve this problem, airplanes are equipped with flight instruments to provide the necessary information for controlling the airplane.

2.4.3.1 Instrument Cross-Check

Pilots must cross-check and interpret the instruments and apply the proper pitch, bank, and power adjustments. Misinterpretation of the instruments or slow cross-checks by the pilot can lead to an airplane upset.

An important factor influencing cross-check technique is the ability of the pilot: "All pilots do not interpret instrument presentations with the same speed; some are faster than others in understanding and evaluating what they see. One reason for this is that the natural ability of pilots varies. Another reason is that the experience levels are different. Pilots who are experienced and fly regularly will probably interpret their instruments more quickly than inexperienced pilots."[3]

Because situations change rapidly during high workload periods, it is crucial for both pilots to monitor the flight path and instruments. In a low workload environment, one pilot can usually monitor the aircraft as there is normally little change. Since it is difficult to stay focused on monitoring during low workload periods, it may be beneficial for pilots to alternate this responsibility. The important thing to remember is that at least one pilot must monitor the aircraft at all times. Effective monitoring allows a pilot to take control of the aircraft before an upset occurs. Some airlines refer to the pilot not flying as the "pilot monitoring" to add emphasis to the importance of this role.

2.4.3.2 Adjusting Attitude and Power

A satisfactory instrument cross-check is only one part of the equation. It is necessary for the pilot to make the correct adjustments to pitch, bank, and power in order to control the airplane. Airplane upsets have occurred when the pilot has made incorrect adjustments. This can happen when the pilot is not familiar with the airplane responses to power adjustments or control inputs. A pilot's control inputs are usually based upon understanding of what the outcome will be. This is called airmanship. On the other hand, if the pilot's control inputs are reactionary, unplanned, and excessive, the airplane reaction may be a complete surprise. A continued divergence from what is expected due to excessive control inputs can lead to an upset. There have also been instances when two pilots have applied opposing inputs simultaneously.

2.4.3.3 Inattention

A review of airplane upsets shows that inattention or neglecting to monitor the airplane performance can result in minor excursions from normal flight regimes to extreme deviations from the norm. Many of the minor upsets can be traced to an improper instrument cross-check; for example, neglecting to monitor all the instruments or fixating on certain instrument indications and not detecting changes in others. Some instrument indications are not as noticeable as others. For example, a slight heading change is not as eye-catching as a 1000-ft/min change in vertical velocity indication.

There are many extreme cases of inattention by the flight crew that have resulted in airplane upset accidents. In one accident, a crew had discussed a recurring autothrottle problem but continued to use the autothrottle. On level-off from a descent, one throttle remained at idle and the other compensated by going to a high power setting. The resulting asymmetric thrust exceeded the autopilot authority and the airplane began to roll. At approximately 50 deg of bank, full pro-roll lateral control wheel was applied. The airplane rolled 168 deg into a steep dive of 78 deg, nose low, and crashed.

3. Source: *Instrument Flight Procedures*. Air Force Manual 11-217, Vol. 1 (1 April 1996).

2.4.3.4 Distraction From Primary Cockpit Duties

"Control the airplane first" has always been a guiding principle in flying. Unfortunately, it is not always followed. In this incident, both pilots were fully qualified as pilot-in-command and were supervising personnel. The captain left the left seat, and the copilot set the airplane on autopilot and went to work on a clipboard on his lap. At this point the autopilot disengaged, possibly with no annunciator light warning. The airplane entered a steep, nosedown, right spiral. The copilot's instrument panel went blank, and he attempted to use the pilot's artificial horizon. However, it had tumbled. In the meantime, the captain returned to his station and recovered the airplane at 6000 ft using needle and ball. This is just one of many incidents where pilots have become distracted. Many times, the distraction is caused by relatively minor reasons, such as caution lights or engine performance anomalies.

2.4.3.5 Vertigo or Spatial Disorientation

Spatial disorientation has been a significant factor in many airplane upset accidents. The definition of spatial disorientation is the inability to correctly orient oneself with respect to the Earth's surface. A flight crew was climbing to about 2000 ft at night during a missed approach from a second instrument landing system (ILS) approach. The weather was instrument meteorological conditions (IMC)—ceiling: 400 ft, visibility: 2 mi, rain, and fog. The airplane entered a spiral to the left. The captain turned the controls over to the first officer, who was unsuccessful in the recovery attempt. The airplane hit trees and was destroyed by ground impact and fire. [NTSB/AAR-92-05]

All pilots are susceptible to sensory illusions while flying at night or in certain weather conditions. These illusions can lead to a conflict between actual attitude indications and what the pilot "feels" is the correct attitude. Disoriented pilots may not always be aware of their orientation error. Many airplane upsets occur while the pilot is busily engaged in some task that takes attention away from the flight instruments. Others perceive a conflict between bodily senses and the flight instruments but allow the airplane to become upset because they cannot resolve the conflict. Unrecognized spatial disorientation tends to occur during task-intensive portions of the flight, while recognized spatial disorientation occurs during attitude-changing maneuvers.

There are several situations that may lead to visual illusions and then airplane upsets. A pilot can experience false vertical and horizontal cues. Flying over sloping cloud decks or land that slopes gradually upward into mountainous terrain often compels pilots to fly with their wings parallel to the slope, rather than straight and level. A related phenomenon is the disorientation caused by the aurora borealis in which false vertical and horizontal cues generated by the aurora result in attitude confusion.

It is beyond the scope of this training aid to expand on the physiological causes of spatial disorientation, other than to alert pilots that it can result in loss of control of an airplane. It should be emphasized that the key to success in instrument flying is an efficient instrument cross-check. The only reliable aircraft attitude information, at night or in IMC, is provided by the flight instruments. Any situation or factor that interferes with this flow of information, directly or indirectly, increases the potential for disorientation. The pilot's role in preventing airplane upsets due to spatial disorientation essentially involves three things: training, good flight planning, and knowledge of procedures. Both pilots must be aware that it can happen, and they must be prepared to control the airplane if the other person is disoriented.

2.4.3.6 Pilot Incapacitation

A first officer fainted while at the controls en route to the Azores, Portugal. He slumped against the controls, and while the rest of the flight crew was removing him from his flight position, the airplane pitched up and rolled to over 80 deg of bank. The airplane was then recovered by the captain. While this is a very rare occurrence, it does happen, and pilots need to be prepared to react properly. Another rare possibility for airplane upset is an attempted hijack situation. Pilots may have very little control in this critical situation, but they must be prepared to recover the airplane if it enters into an upset.

2.4.3.7 Improper Use of Airplane Automation

The following incident describes a classic case of improper use of airplane automation. "During an approach with autopilot 1 in command mode, a missed approach was initiated at 1500 ft. It is undetermined whether this was initiated by the pilots; however, the pilot attempted to counteract the autopilot-commanded pitchup by pushing forward on the control column. Normally, pushing on the control column would disengage the autopilot, but automatic disconnect was inhibited in go-around mode in this model airplane. As a result of the control column inputs, the autopilot trimmed the stabilizer to 12 deg, nose up, in order to maintain the programmed go-around profile. Meanwhile, the pilot-applied control column forces caused the elevator to deflect 14 deg, nose down. The inappropriate pilot-applied control column forces resulted in three extreme pitchup stalls before control could be regained. The airplane systems operated in accordance with design specifications." [FSF, Flight Safety Digest 1/92]

The advancement of technology in today's modern airplanes has brought us flight directors, autopilots, autothrottles, and flight management systems. All of these devices are designed to reduce the flight crew workload. When used properly, this technology has made significant contributions to flight safety. But technology can include complexity and lead to trust and eventual complacency. The systems can sometimes do things that the flight crew did not intend for them to do. Industry experts and regulators continue to work together to find the optimal blend of hardware, software, and pilot training to ensure the highest possible level of system performance—which centers on the human element.

2.4.3.8 Pilot Techniques—PIO Avoidance/ Recovery

All aircraft are developed and certified so as to ensure that their control is easy and well-behaved throughout their operating envelope. Testing to ensure these good handling characteristics assumes that pilots are utilizing typical piloting techniques during routine line operations. In some circumstances, however, a pilot may find that his own control inputs can cause unwanted aircraft motion that could lead to an upset or loss of control. Known as pilot-induced oscillations (PIO), this condition occurs when a pilot's commands become out of phase with the aircraft's motion.

There could be a number of technical or human factors causes for this condition. Examples may include, an over-speed, an out-of-trim condition, or some flight control system failures. To the pilot, all of the causes result in the aircraft not responding as quickly or as aggressively as the pilot desires. This leads to pilot inputs that grow increasingly out of phase with the aircraft response. Pilots are most susceptible to PIO when they put in rapid inputs under stress, such as during upset recoveries. The net effect is that pilot inputs may produce unpredictable aircraft motion with accompanied pitch or roll oscillations. Sometimes, the pilot flying may be so involved in regaining control, he may not be aware of this oscillatory motion. In this case, the pilot not flying may need to verbalize the PIO condition. In any case, the oscillations/coupling can be stopped by neutralizing, or releasing, the controls for a long enough period to break the cycle.

2.4.4 Combination of Causes

A single cause of an airplane upset can be the initiator of other causes. In one instance, a possible inadvertent movement of the flap/slat handle resulted in the extension of the leading edge slats. The captain's initial reaction to counter the pitchup was to exert forward control column force; the control force when the autopilot disconnected resulted in an abrupt airplane nosedown elevator command. Subsequent commanded elevator movements to correct the pitch attitude induced several violent pitch oscillations. The captain's commanded elevator movements were greater than necessary because of the airplane's light control force characteristics. The oscillations resulted in a loss of 5000 ft of altitude. The maximum nosedown pitch attitude was greater than 20 deg, and the maximum normal accelerations were greater than 2 g and less than 1 g.

This incident lends credence to the principle used throughout this training aid: ***Reduce the level of automation while initiating recovery; that is, disconnect the autopilot and autothrottle, and do not let the recovery from one upset lead to another by excessive use of the controls.***

2.5 Swept-Wing Airplane Fundamentals for Pilots

Aircraft are designed, tested, and certified based on accepted assumptions of how pilots will oper-

ate them, together with various environmental and technical constraints (e.g., gusts, engine failure dynamics). These assumptions drive the regulatory certification requirements and are validated through in-service experience. The certification flight test process examines the entire flight envelope of the aircraft, including that area beyond which the airline pilot normally operates. Examples would be a fully stalled aircraft or airspeed exceeding V_{mo}. The process even explores how the aircraft could possibly be inappropriately operated; however, the testing assumes fundamental flying skills are known and understood. A primary assumption regarding pilot inputs is that they are based on control inputs that are measured (the result of experience), analyzed, then fine-tuned to achieve a desired result. Exaggerated rates and amounts of control deflection (overcontrolling) may cause an accelerating divergence of flight path control until the input is countered.

2.5.1 Flight Dynamics

In understanding the flight dynamics of large, swept-wing transport airplanes, it is important to first understand what causes the forces and moments acting on the airplane and then move to what kinds of motion these forces cause. Finally, with this background, one can gain an understanding of how a pilot can control these forces and moments in order to direct the flight path.

Pilots *are expected to* make control inputs based on desired aircraft reaction. Control deflections at one point in the flight envelope might not be appropriate in another part of the flight envelope. Pilots must have a fundamental understanding of flight dynamics in order to correctly make these choices. They *should not* make mechanical control deflections and rote reactions to dynamic situations that require an understanding of these flight fundamentals.

Newton's first law states that an object at rest will tend to stay at rest, and an object in motion will tend to stay in motion in a straight line, unless acted on by an external force. This definition is fundamental to all motion, and it provides the foundation for all discussions of flight mechanics. A careful examination of this law reveals an important subtlety, which is the reference to motion in a straight line. If an airplane in motion is to deviate from a straight line, there must be a force, or a combination of forces, imposed to achieve the desired trajectory. The generation of the forces is the subject of aerodynamics (to be discussed later). The generation of forces requires energy.

2.5.2 Energy States

A pilot has three sources of energy available to manage or manipulate to generate aerodynamic forces and thus control the flight path of an airplane.

The term "energy state" describes how much of each kind of energy the airplane has available at any given time. Pilots who understand the airplane energy state will be in a position to know instantly what options they may have to maneuver their airplane. The three sources of energy available to the pilot are

a. Kinetic energy, which increases with increasing airspeed.
b. Potential energy, which is proportional to altitude.
c. Chemical energy, from the fuel in the tanks.

The airplane is continuously expending energy; in flight, this is because of drag. (On the ground, wheel brakes and thrust reversers, as well as friction, dissipate energy.) This drag energy in flight is usually offset by using some of the stored chemical energy—by burning fuel in the engines.

During maneuvering, these three types of energy can be traded, or exchanged, usually at the cost of additional drag. This process of consciously manipulating the energy state of the airplane is referred to as "energy management." Airspeed can be traded for altitude, as in a zoom-climb. Altitude can be traded for airspeed, as in a dive. Stored energy can be traded for either altitude or airspeed by advancing the throttles to command more thrust than required for level flight. The trading of energy must be accomplished, though, with a view toward the final desired energy state. For example, while altitude can be traded for airspeed by diving the airplane, care must be taken in selecting the angle of the dive so that the final desired energy state will be captured.

This becomes important when the pilot wants to generate aerodynamic forces and moments to maneuver the airplane. Only kinetic energy (airspeed) can generate aerodynamic forces and maneuver capability. Kinetic energy can be traded for potential energy (climb). Potential energy can only be

converted to kinetic energy. Chemical energy can be converted to either potential or kinetic energy, but only at specified rates. These energy relationships are shown in Figure 10.

High-performance jet transport airplanes are designed to exhibit very low drag in the cruise configuration. This means that the penalty for trading airspeed for altitude is relatively small. Jet transport airplanes are also capable of gaining speed very rapidly in a descent. The pilot needs to exercise considerable judgment in making very large energy trades. Just as the level flight acceleration capability is limited by the maximum thrust of the engines, the deceleration capability is limited by the ability to generate very large drag increments. For high-performance jet transport airplanes, the ability to generate large decelerating drag increments is often limited. The pilot always should be aware of these limitations for the airplane being flown. A very clean airplane operating near its limits can easily go from the low-speed boundary to and through the high-speed boundary very quickly.

The objective in maneuvering the airplane is to manage energy so that kinetic energy stays between limits (stall and placards), the potential energy stays within limits (terrain to buffet altitude), and chemical energy stays above certain thresholds (not running out of fuel). This objective is especially important during an inadvertent upset and the ensuing recovery.

In managing these energy states and trading between the various sources of energy, the pilot does not directly control the energy. The pilot controls the orientation and magnitude of the various forces acting on the airplane. These forces result in accelerations applied to the airplane. The result of these accelerations is a change in the orientation of the airplane and a change in the direction or magnitude, or both, of the flight path vector. Ultimately, velocity and altitude define the energy state.

This process of controlling forces to change accelerations and produce a new energy state takes time. The amount of time required is a function of the *mass* of the airplane and the *magnitude* of the applied forces, and it is also governed by Newton's laws. Airplanes of larger mass generally take longer to change orientation than do smaller ones. The longer time requires the pilot to plan ahead more in a large-mass airplane and make sure that the actions taken will achieve the final desired energy state.

2.5.3 Load Factors

Load factor in the realm of flight mechanics is a measure of the acceleration being experienced by the airplane. By Newton's second law,

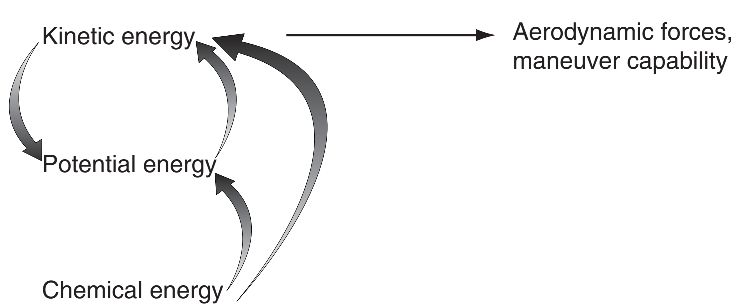
force = mass x acceleration

Since the airplane has mass, if it is being accelerated there must be a force acting on it. Conversely, if there is a force acting on an airplane, it will accelerate. In this case, acceleration refers to a change in either magnitude or direction of the velocity. This definition of acceleration is much more broad than the commonplace reference to acceleration as simply "speeding up." Acceleration has dimensions (length/time^2). It is convenient to refer to acceleration by comparing it to the acceleration due to gravity (which is 32.2 ft/s^2 or 9.81 m/s^2). Acceleration is expressed in this way as units of gravity (g).

In addition, the acceleration (or load factor in g's) is typically discussed in terms of components relative to the principal axes of the airplane:

a. Longitudinal (fore and aft, typically thought of as speed change).
b. Lateral (sideways).
c. Vertical (or normal).

Figure 10 Energy Relationships



Frequently, load factor is thought of as being only perpendicular to the floor of the airplane. But the force, and thus the acceleration, may be at any orientation to the airplane, and the vertical, or normal, load factor represents only one component of the total acceleration. In sideslip, for example, there is a sideways acceleration, and the pilot feels pushed out of the seat sideways. In a steep climb or a rapid acceleration, the pilot feels forced back into the seat.

In level flight, the vertical load factor is one times the acceleration due to gravity, or 1.0 (Fig. 11). This means that the wing is producing lift equal to 1.0 times the weight of the airplane, and it is oriented in a direction opposed to the gravity vector. In a pull-up, the load factor is above 1.0 (Fig. 12).

In the example in Figure 12, the load factor is 2.0. That is, the force generated by the airplane (wings, fuselage, etc.) is twice that of gravity. Also note that the flight path is now curved. Newton's first law says that an object will continue in a straight line unless acted on by a force. In this case, the lift force is acting in a perpendicular direction to the velocity, and the resulting flight path is curved.

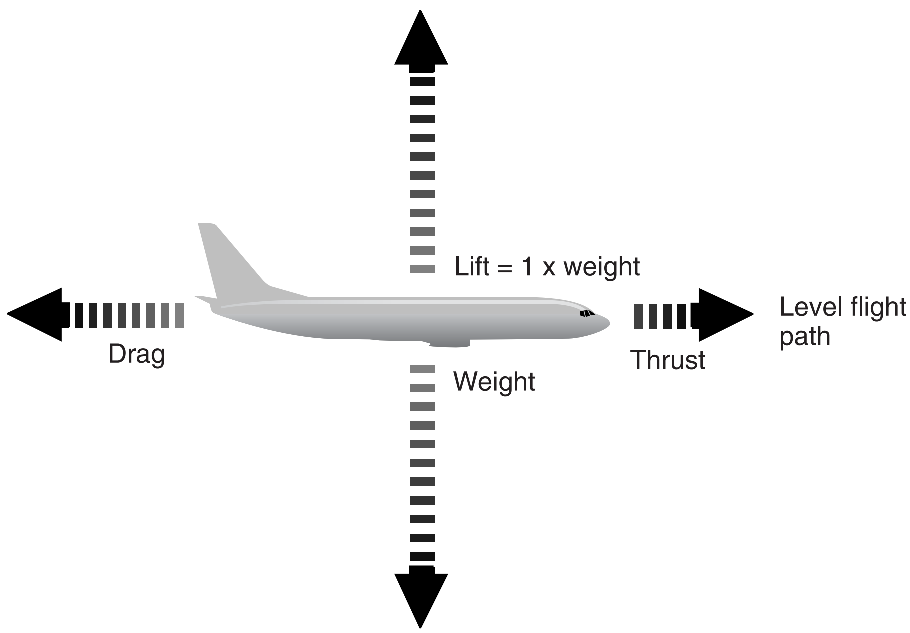


Figure 11
Four Forces of Flight

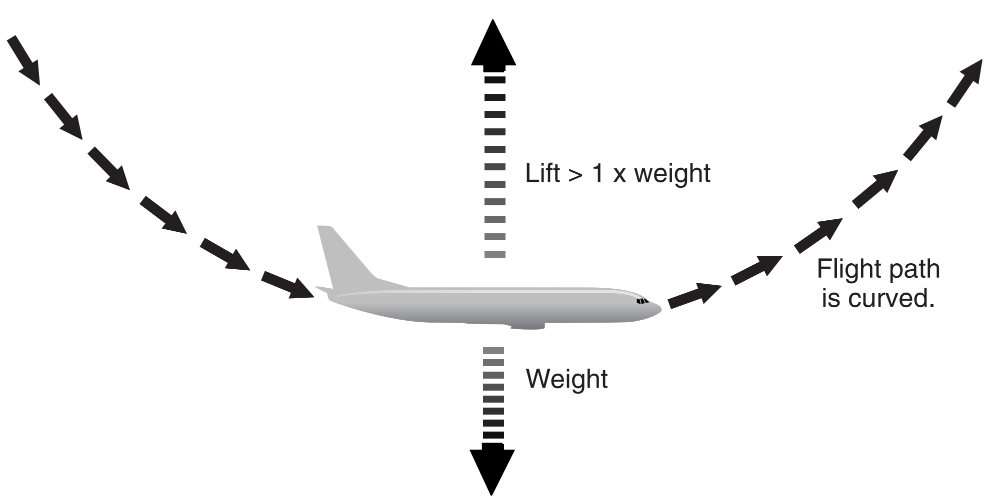


Figure 12
Airplane in Pull-Up

In a sustained vertical climb along a straight line, the thrust must be greater than the weight and drag. The load factor perpendicular to the airplane floor must be zero (Fig. 13a).

If it were anything but zero, the flight path would not be a straight line (Fig. 13b).

Note that the acceleration is a result of the sum of all forces acting on the airplane. One of those forces is always gravity. Gravity always produces an acceleration directed toward the center of the Earth. The airplane attitude determines the direction of the gravitational force with respect to the airplane. Aerodynamic forces are produced as a result of orientation and magnitude of the velocity vector relative to the airplane, which is reduced into angles of attack and sideslip. (Refer to Sec. 2.5.5, "Aerodynamics", for a detailed discussion.) It is the direction and speed of the airplane through the air that results in aerodynamic forces (e.g., straight ahead or sideways, fast or slow). It is the orientation of the airplane to the center of the Earth that determines the orientation of the gravity vector.

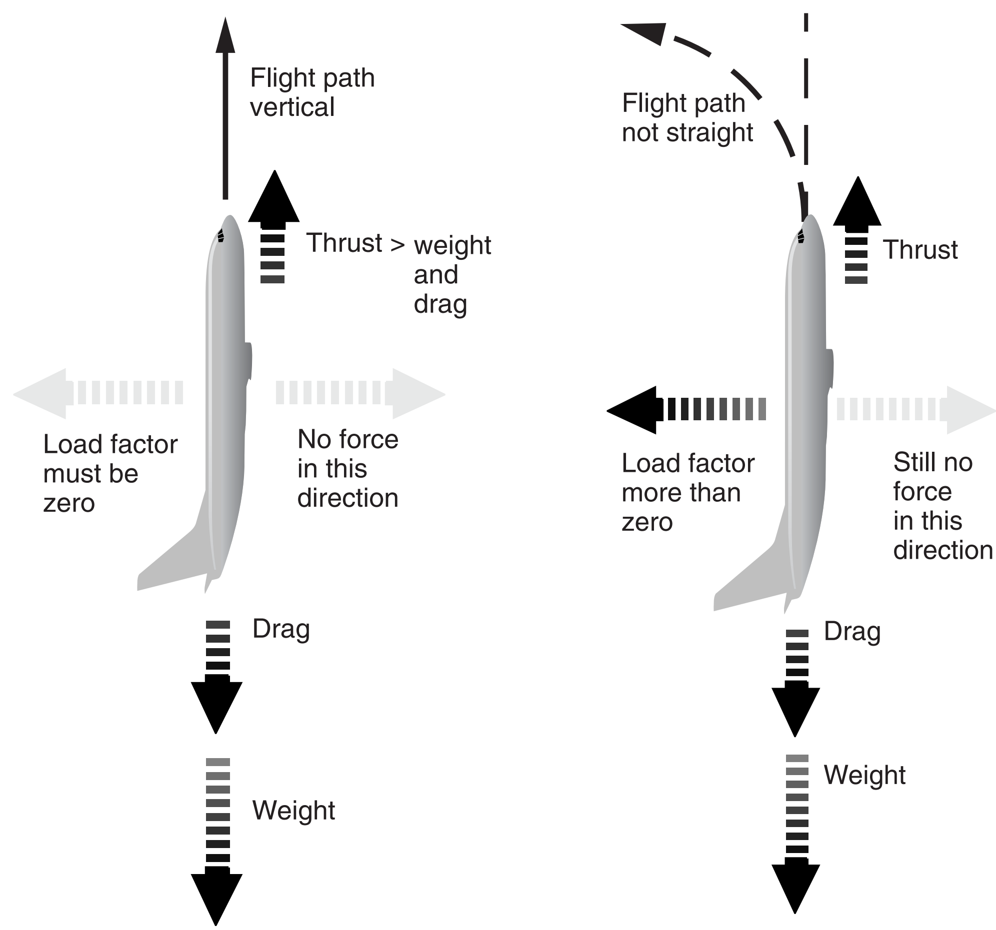
Current jet transport airplanes are certificated to withstand normal vertical load factors from –1.0 to 2.5 g in the cruise configuration. Figure 14 is a typical v-n diagram for a transport airplane ("v" for velocity, "n" for number of g's acceleration). In addition to the strength of the structure, the handling qualities are demonstrated to be safe within these limits of load factor. This means that a pilot should be able to maneuver safely to and from these load factors at these speeds without needing exceptional strength or skill.

Pilots should be aware of the various weight, configuration, altitude, and bank angle specifics of the diagrams for the particular airplane they fly and of the limitations imposed by them.

Design maneuver speed, V_A, is identified in the Airplane Flight Manual (AFM). It was a design condition the manufacturer used to demonstrate

Figure 13a Airplane Vertical With Forces Balanced

Figure 13b (right) Airplane Vertical With Forces Unbalanced



the structural capability of the airplane. It is used to validate design criteria, and because it varies with altitude, it is of limited use to a pilot. Only single flight control inputs are considered and calculated. Control reversals are not considered in design and certification and must be avoided. We recommend that pilots use turbulence penetration speed as a reference speed above which abrupt control inputs should be avoided.

V_A should not be confused with minimum or configuration maneuver speed, which is the recommended minimum speed for maneuvering at various flap/slat configurations. On many modern airplanes, minimum or configuration maneuver speed is the minimum speed that autothrottles/autothrust will control to.

2.5.4 Aerodynamic Flight Envelope

Airplanes are designed to be operated in well-defined envelopes of airspeed and altitude. The operational limits for an airplane—stall speeds, placarded maximum speeds and Mach numbers, and maximum certificated altitudes—are in the AFM for each individual airplane. Within these limits, the airplanes have been shown to exhibit safe flightcharacteristics.

Manufacturing and regulatory test pilots have evaluated the characteristics of airplanes in conditions that include inadvertent exceedances of these operational envelopes to demonstrate that the airplanes can be returned safely to the operational envelopes. Figure 15 depicts a typical flight envelope. M_{MO} and V_{MO} are the operational limitations,

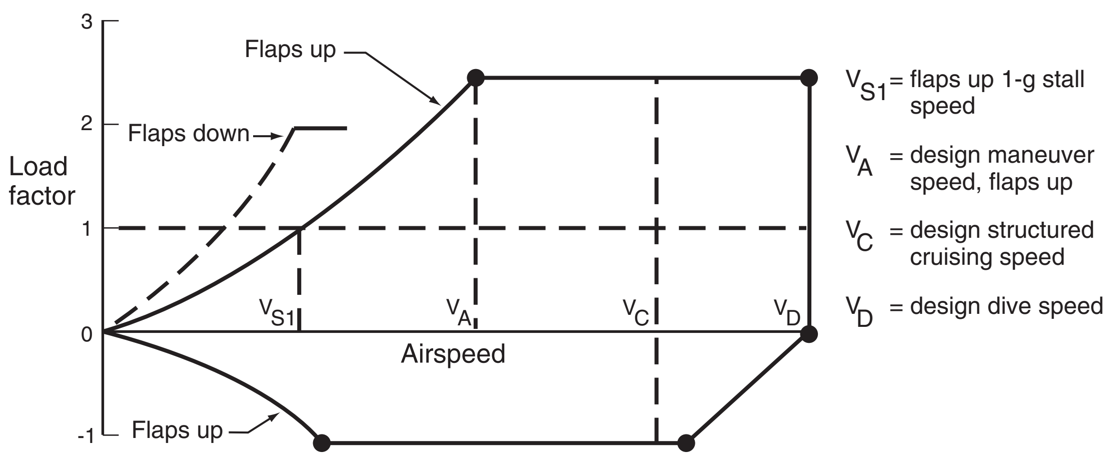


Figure 14
Load Factor Envelope Showing Speeds and Load Factors

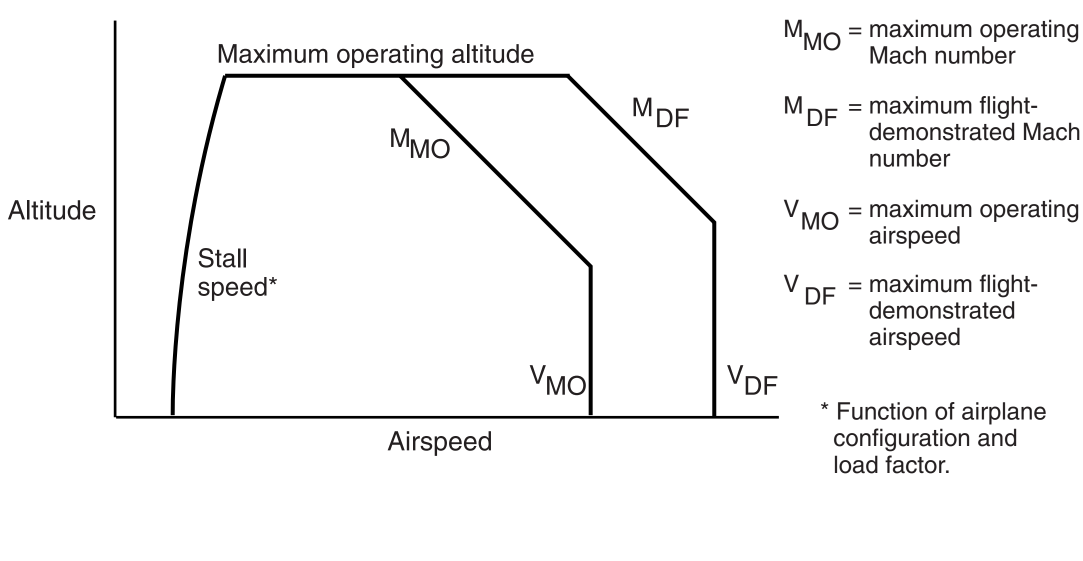


Figure 15
Aerodynamic Flight Envelope

but the figure also shows the relationship to M_{DF} and V_{DF}, the maximum dive speeds demonstrated in flight test. These are typically 0.05 to 0.07 Mach and 50 kn higher than the operational limits. In the region between the operational envelope and the dive envelope, the airplane is required to exhibit safe characteristics. Although the characteristics are allowed to be degraded in that region from those within the operational flight envelope, they are shown to be adequate to return the airplane to the operational envelope if the airplane is outside the operational envelope.

2.5.5 Aerodynamics

Aside from gravity and thrust forces, the other forces acting on an airplane are generated as a result of the changing pressures produced on the surfaces that result in turn from the air flowing over them. A brief review of basic fundamental aerodynamic principles will set the stage for discussion of airplane upset flight dynamics.

2.5.5.1 Angle of Attack and Stall

Most force-generating surfaces on modern jet transport airplanes are carefully tailored to generate lifting forces efficiently. Wings and tail surfaces all produce lift forces in the same way. Figure 16 shows a cross section of a lifting surface and the familiar definition of angle of attack. The lift force in pounds generated by a surface is a function of the angle of attack, the dynamic pressure (which is proportional to the air density and the square of the true airspeed) of the air moving around it, and the size of the surface.

It is important to understand the dependence of lift on angle of attack. Figure 17 shows how lift varies with angle of attack for constant speed and air density. Important features of this dependency include the fact that at zero angle of attack, lift is not zero. This is because most lifting surfaces are cambered. Further, as angle of attack is increased, lift increases proportionally, and this increase in lift is normally quite linear. At higher angles of attack, however, the lift due to angle of attack

Figure 16
Airfoil at Angle of Attack

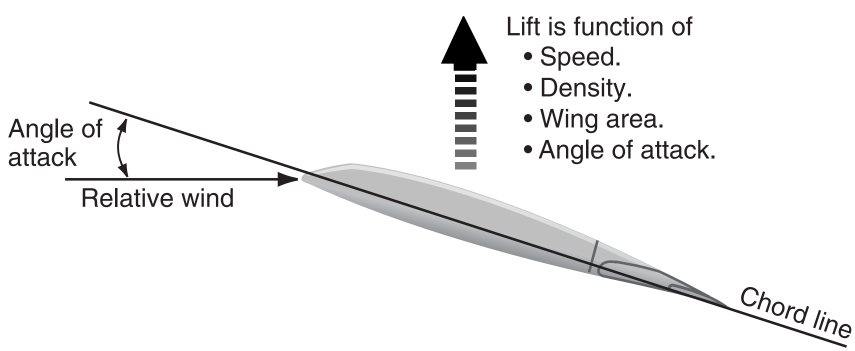
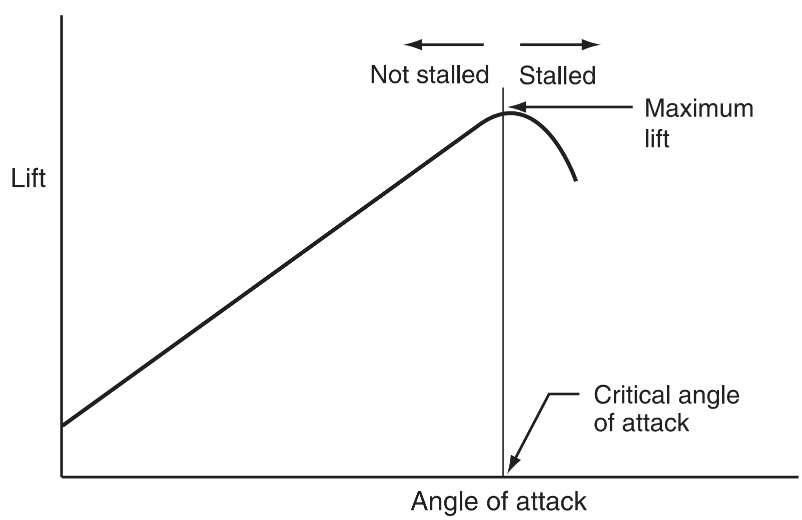


Figure 17
Lift at Angle of Attack



behaves differently. Instead of increasing with an increase in angle of attack, it decreases. At this critical angle of attack, the air moving over the upper surface can no longer remain attached to the surface, the flow breaks down, and the surface is considered stalled.

It is necessary to understand that this breakdown of the flow and consequent loss of lift is dependent only on the angle of attack of the surface. ***Exceed the critical angle of attack and the surface will stall, and lift will decrease instead of increasing. This is true regardless of airplane speed or attitude.*** To sustain a lifting force on the aerodynamic surfaces, the pilot must ensure that the surfaces are flown at an angle of attack below the stall angle, that is, avoid stalling the airplane.

Depending on the context in which it is used, aerodynamicists use the term "angle of attack" in a number of ways. Angle of attack is always the angle between the oncoming air, or relative wind, and some reference line on the airplane or wing. Sometimes it is referenced to the chord line at a particular location on the wing; sometimes to an "average" chord line on the wing; other times it is referenced to a convenient reference line on the airplane, like the body reference x axis. Regardless of the reference, the concept is the same as are the consequences: exceed the critical angle of attack and the lifting surfaces and wind will separate, resulting in a loss of lift on those surfaces. Frequently the term "airplane angle of attack" is used to refer to the angle between the relative wind and the longitudinal axis of the airplane. In flight dynamics, this is frequently reduced to simply "angle of attack."

Angle of attack can sometimes be confusing because there is not typically an angle-of-attack indicator in most commercial jet transport airplanes. The three angles usually referred to in the longitudinal axis are

a. Angle of attack.
b. Flight path angle.
c. Pitch attitude.

These three angles and their relationships to each other are shown in Figure 18.

Pitch attitude, or angle, is the angle between the longitudinal axis of the airplane and the horizon. This angle is displayed on the attitude indicator or artificial horizon.

The flight path angle is the angle between the flight path vector and the horizon. This is also the climb (or descent angle). On the newest generation jet transports, this angle can be displayed on the primary flight display (PFD), as depicted in Figure 18. Flight path angle can also be inferred from the vertical speed indicator (VSI) or altimeter, if the ground speed is known. Many standard instrument departures require knowledge of flight path angle in order to ensure obstacle clearance.

Angle of attack is also the difference between the pitch attitude and the flight path angle with no vertical wind component. The angle of attack determines whether the aerodynamic surfaces on the airplane are stalled or not.

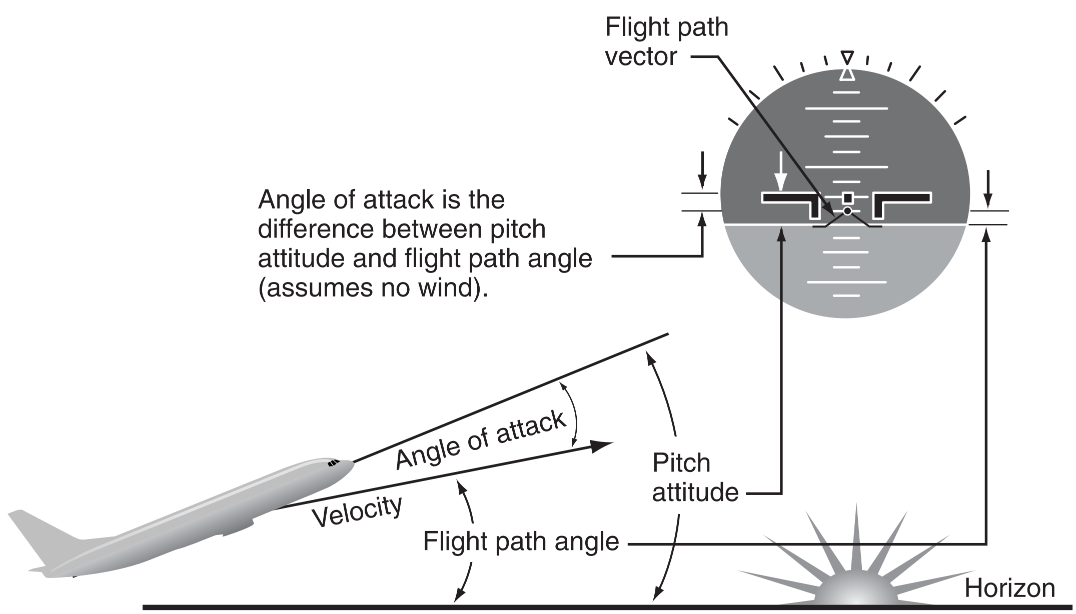


Figure 18
Pitch Attitude, Flight Path Angle, and Angle of Attack

The important point is that when the angle of attack is above the stall angle, the lifting capability of the surface is diminished. This is true regardless of airspeed. An airplane wing can be stalled at any airspeed. An airplane can be stalled in any attitude. If the angle of attack is greater than the stall angle, the surface will stall. Figure 19 indicates that regardless of the airspeed or pitch attitude of the airplane, the angle of attack determines whether the wing is stalled.

A stall is characterized by any or a combination of the following:

a. Buffeting, which could be heavy.
b. Lack of pitch authority.
c. Lack of roll control.
d. Inability to arrest descent rate.

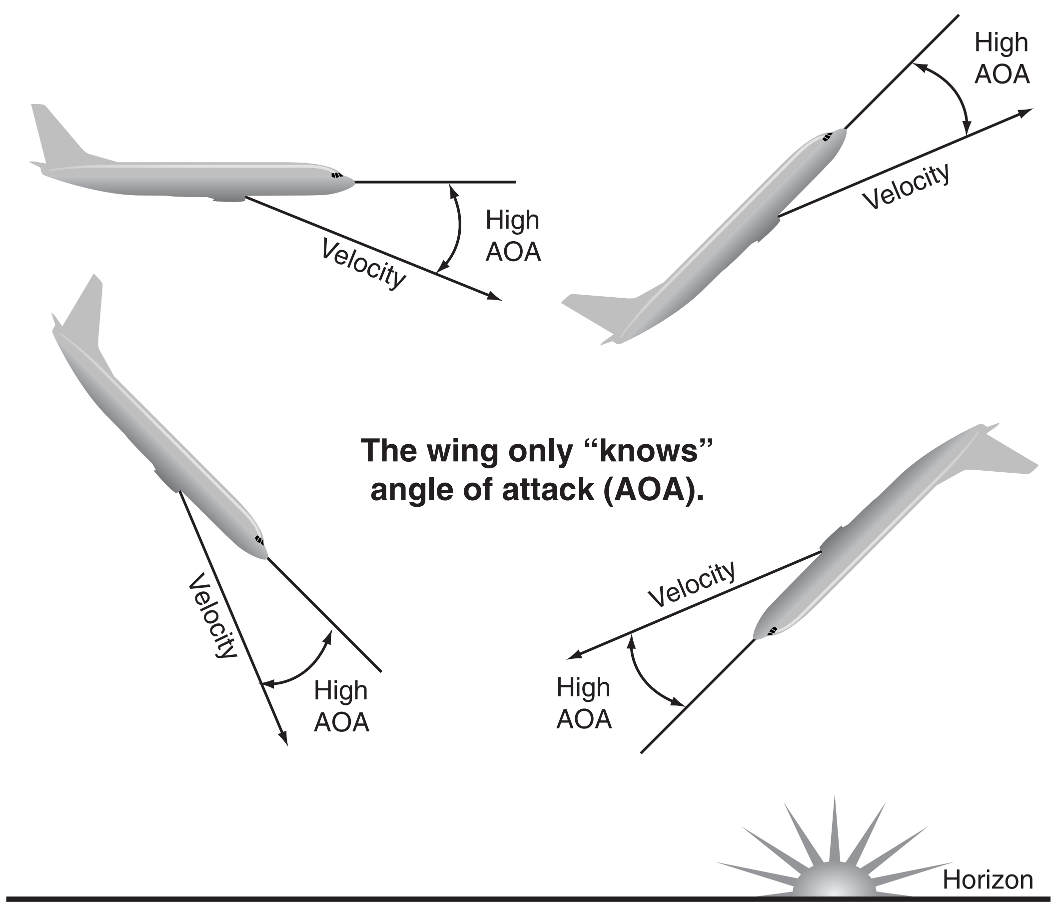
These characteristics are usually accompanied by a continuous stall warning. A stall must not be confused with an approach-to-stall warning that occurs before the stall and warns of an approaching stall. An approach to stall is a controlled flight maneuver. However, a full stall is an out-of-control condition, but it is recoverable.

Stall speeds are published in the AFM for each transport airplane, giving the speeds at which the airplane will stall as a function of weight. This information is very important to the pilot, but it must be understood that the concept of stall speed is very carefully defined for specific conditions:

a. Trim at 1.3 V_S.
b. Forward CG.
c. Low altitudes.
d. Deceleration rate of 1 kn/s.
e. Wings level.
f. Approximately 1-g flight.

Under normal conditions, the wings are level or near level, and the normal load factor is very near 1.0. Under these conditions, the published stall speeds give the pilot an idea of the proximity to stall. In conditions other than these, however, the speed at stall is not the same as the "stall speed." Aerodynamic stall depends only on angle of attack, and it has a specific relationship to stall speed only under the strict conditions previously noted. Many upsets are quite dynamic in nature and involve elevated load factors and large speed-change rates. Pilots should not expect the airplane

Figure 19 Several Pitch Attitudes and Stall Angle of Attack



to remain unstalled just because the indicated airspeed is higher than AFM chart speeds, because the conditions may be different.

All modern jet transports are certified to exhibit adequate warning of impending stall to give the pilot opportunity to recover by decreasing the angle of attack. Whether this warning is by natural aerodynamic buffet or provided by a stick shaker or other warning devices, it warns the pilot when the angle of attack is getting close to stall. Moreover, the warning is required to be in a form other than visual. The pilot need not look at a particular instrument, gauge, or indicator. The warning is tactile: the pilot is able to feel the stall warning with enough opportunity to recover promptly. Pilots need to be especially cognizant of stall warning cues for the particular airplanes they fly. The onset of stall warning should be taken as an indication to not continue to increase the angle of attack.

The angle of attack at which a wing stalls reduces with increasing Mach so that at high Mach (normally, high altitude), an airplane may enter an accelerated stall at an angle of attack that is less than the angle of attack for stalling at lower Mach numbers.

2.5.5.2 Camber

Camber refers to the amount of curvature evident in an airfoil shape. Camber is illustrated in Figure 20. The mean camber line is a line connecting the midpoints of upper and lower surfaces of an airfoil. In contrast, the chord line is a straight line connecting the leading and trailing edges.

Technical aerodynamicists have defined camber in a variety of ways over the years, but the reason for introducing camber has remained the same: airfoils with camber are more efficient at producing lift than those without. Importantly, airfoils with specific kinds of camber at specific places are more efficient than those of slightly different shape.

Airplanes that must produce lift as efficiently up as well as down, such as competition aerobatics airplanes, usually employ symmetrical airfoils. These work well, but they are not as efficient for cruise flight. Efficient, high-speed airplanes often employ exotic camber shapes because they have been found to have beneficial drag levels at high speeds. Depending on the mission the airplane is intended to fly, the aerodynamic surfaces are given an optimized camber shape. While both cambered and uncambered surfaces produce lift at angle of attack, camber usually produces lift more efficiently than angle of attack alone.

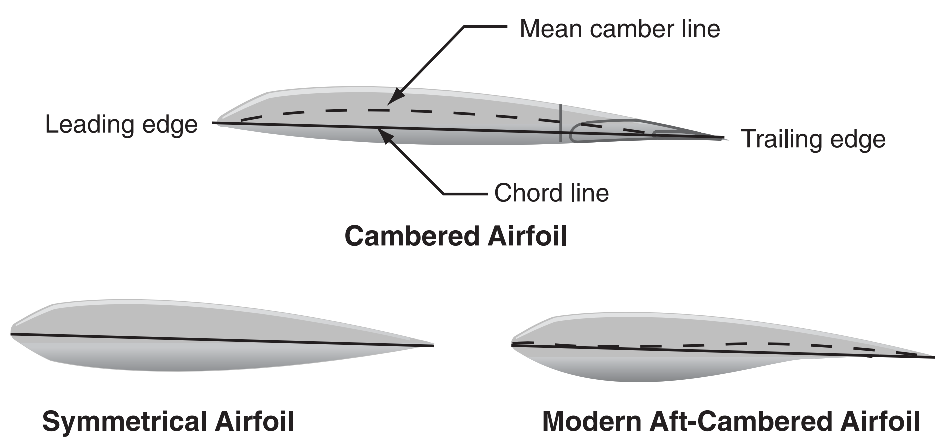


Figure 20
Camber Definition

2.5.5.3 Control Surface Fundamentals

Trailing edge control surfaces such as ailerons, rudders, and elevators provide a way of modulating the lift on a surface without physically changing the angle of attack. These devices work by altering the camber of the surfaces. Figure 21 shows undeflected and deflected control surfaces.

The aerodynamic effect is that of increasing the lift at constant angle of attack for trailing edge down deflection. This is shown in Figure 22. The price paid for this increased lift at constant angle of attack is a reduced angle of attack for stall. Note that for larger deflections, even though the lift is greater, the stall angle of attack is lower than that at no deflection.

The important point is that increasing camber (downward deflection of ailerons, for example) lowers the angle of attack at which stall occurs. Large downward aileron deflections at very high angles of attack could induce air separation over that portion of the wing. Reducing the angle of attack before making large aileron deflections will help ensure that those surfaces are as effective as they can be in producing roll.

2.5.5.3.1 Spoiler-Type Devices

Spoilers, sometimes referred to as “speedbrakes” on large transport airplanes, serve a dual purpose of “spoiling” wing lift and generating additional drag. By hinging upwards from the wing upper surface, they generate an upper surface discontinuity that the airflow cannot negotiate, and they separate, or stall, the wing surface locally. Figure 23 depicts spoiler operation with both flaps up and flaps down. The effectiveness of spoiler devices depends on how much lift the wing is generating (which the spoiler will “spoil”). If the wing is not producing much lift to begin with, spoiling it will not produce much effect. If the wing is producing large amounts of lift, as is the case with the flaps extended and at moderate angles of attack, the spoilers become very effective control devices because there is more lift to spoil.

Because spoilers depend on there being some lift to “spoil” in order to be effective, they also lose much of their effectiveness when the wing is in a stalled condition. If the flow is already separated, putting a spoiler up will not induce any more separation. As was the case with aileron control at high angles of attack, it is important to know that

Figure 21 Deflected Surfaces

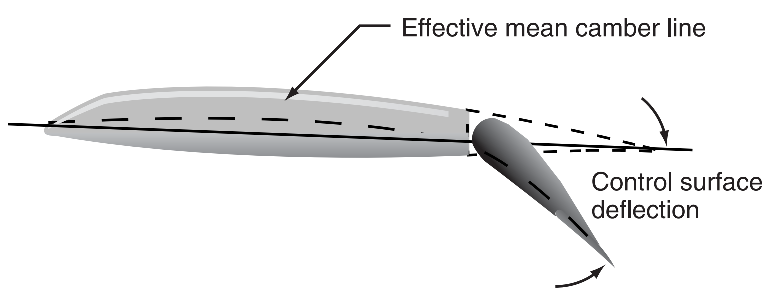
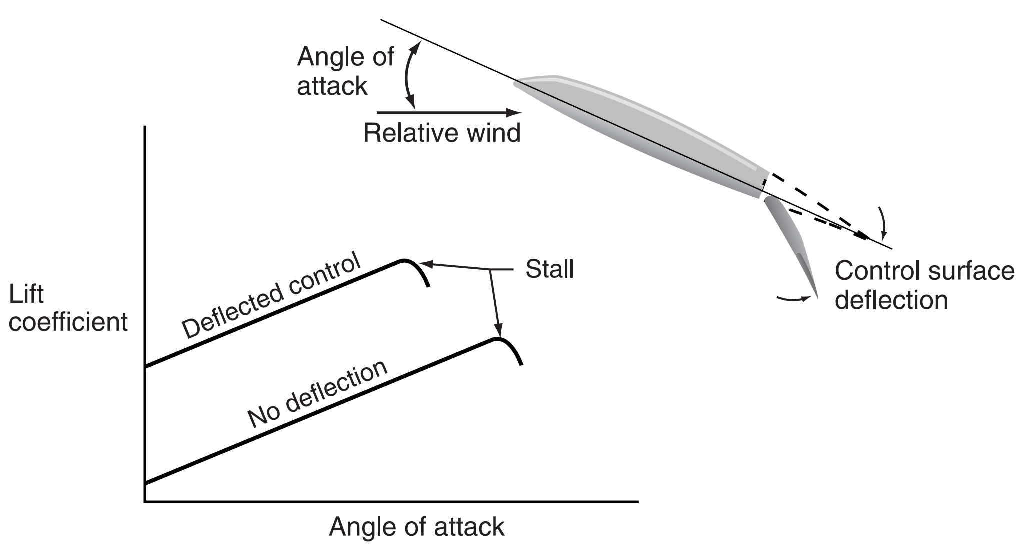


Figure 22 Lift Characteristics for Deflected Trailing Edge Surfaces



the wing must be unstalled in order for the aerodynamic controls to be effective.

2.5.5.3.2 Trim

Aerodynamicists refer to "trim" as that condition in which the forces on the airplane are stabilized and the moments about the center of gravity all add up to zero. Pilots refer to "trim" as that condition in which the airplane will continue to fly in the manner desired when the controls are released. In reality, both conditions must be met for the airplane to be "in trim." In the pitch axis, aerodynamic, or moment, trim is achieved by varying the lift on the horizontal tail/elevator combination to balance the pitching moments about the center of gravity. Once the proper amount of lift on the tail is achieved, means must be provided to keep it constant. Traditionally, there have been three ways of doing that: fixed stabilizer/trim tab, all-flying tail, and trimmable stabilizer.

In the case of the fixed stabilizer/trim tab configuration, the required tail load is generated by deflecting the elevator. The trim tab is then deflected in such a way as to get the aerodynamics of the tab to hold the elevator in the desired position. The airplane is then in trim (because the required load on the tail has been achieved) and the column force trim condition is met as well (because the tab holds the elevator in the desired position). One side effect of this configuration is that when trimmed near one end of the deflection range, there is not much more control available for maneuvering in that direction (Fig. 24).

In the case of the all-flying tail, the entire stabilizer moves as one unit in response to column commands. This changing of the angle of attack of the stabilizer adjusts the tail lift as required to balance the moments. The tail is then held in the desired position by an irreversible flight control system (usually hydraulic). This configuration requires a very powerful and fast-acting control system to

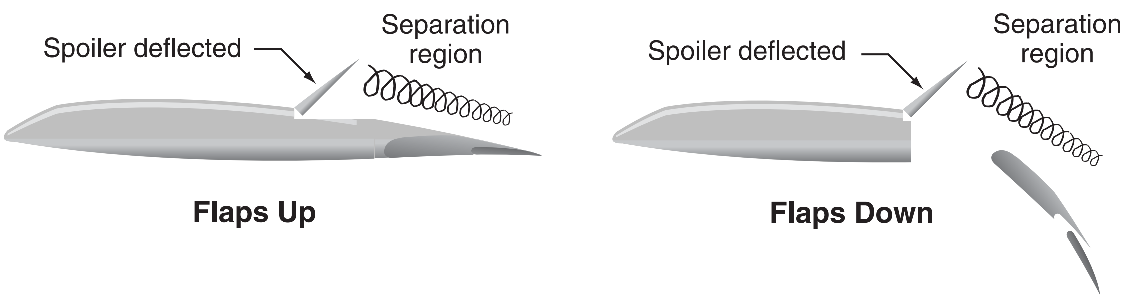


Figure 23
Spoiler Devices

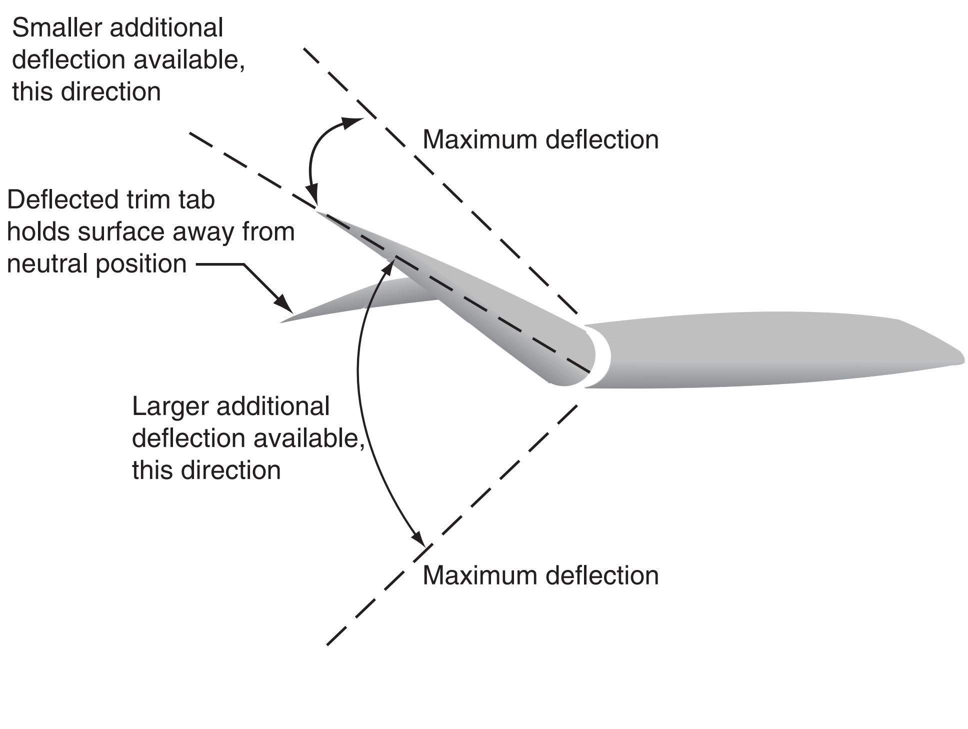


Figure 24
Typical Trimmable Tails

move the entire tail in response to pilot inputs, but it has been used quite successfully on commercial jet transport airplanes.

In the case of the trimmable stabilizer, the proper pitching moment is achieved by deflecting the elevator and generating the required lift on the tail. The stabilizer is then moved (changing its angle of attack) until the required tail lift is generated by the stabilizer with the elevator essentially at zero deflection. A side effect of this configuration is that from the trimmed condition, full elevator deflection is available in either direction, allowing a much larger range of maneuvering capability. This is the configuration found on most high-performance airplanes that must operate through a very wide speed range and that use very powerful high-lift devices (flaps) on the wing.

Knowing that in the trimmed condition the elevator is nearly faired or at zero deflection, the pilot instantly knows how much control power is available in either direction. This is a powerful tactile cue, and it gives the pilot freedom to maneuver without the danger of becoming too close to surface stops.

2.5.5.4 Lateral and Directional Aerodynamic Considerations

Aerodynamically, anti-symmetric flight, or flight in sideslip, can be quite complex. The forces and moments generated by the sideslip can affect motion in all three axes of the airplane. As will be seen, sideslip can generate strong aerodynamic rolling moments as well as yawing moments. In particular, the magnitude of the coupled roll-due-to-sideslip is determined by several factors.

2.5.5.4.1 Angle of Sideslip

Just as airplane angle of attack is the angle between the longitudinal axis of the airplane and the relative wind as seen in a profile view, the sideslip angle is the angle between the longitudinal axis of the airplane and the relative wind, seen this time in the plan view (Fig. 25). It is a measure of whether the airplane is flying straight into the relative wind.

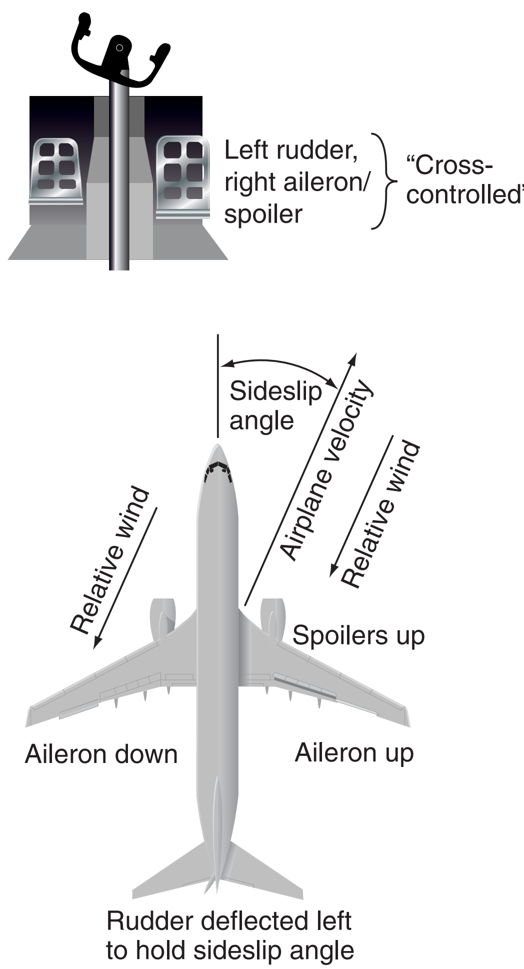


Figure 25
Angle of Sideslip

With the exception of crosswind landing considerations requiring pilot-commanded sideslip, commercial transport airplanes are typically flown at or very near zero sideslip. This usually results in the lowest cruise drag and is most comfortable for passengers, as the sideways forces are minimized.

For those cases in which the pilot commands a sideslip, the aerodynamic picture becomes a bit more complex. Figure 25 depicts an airplane in a commanded nose-left sideslip. That is, the velocity vector is not aligned with the longitudinal axis of the airplane, and the relative wind is coming from the pilot's right.

One purpose of the vertical tail is to keep the nose of the airplane "pointed into the wind," or make the tail follow the nose. When a sideslip angle is developed, the vertical tail is at an angle of attack and generates "lift" that points sideways, tending to return the airplane to zero sideslip. Commercial jet transport airplanes are certificated to exhibit static directional stability that tends to return the airplane to zero sideslip when controls are released or returned to a neutral position. In order to hold a sideslip condition, the pilot must hold the rudder in a deflected position (assuming symmetrical thrust).

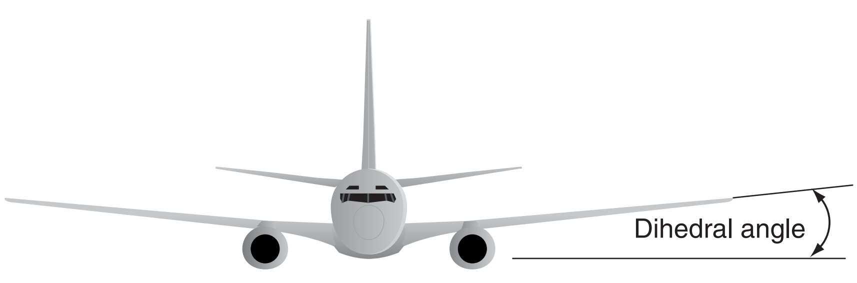
2.5.5.4.2 Wing Dihedral Effects

Dihedral is the positive angle formed between the lateral axis of an airplane and a line that passes through the center of the wing, as depicted in Figure 26. Dihedral contributes to the lateral stability of an airplane, and commercial jet transport airplanes are certificated to exhibit static lateral stability. A wing with dihedral will develop stable rolling moments with sideslip. If the relative wind comes from the side, the wing into the wind is subject to an increase in lift. The wing away from the wind is subject to a decrease in angle of attack and develops a decrease in lift. The changes in lift effect a rolling moment, tending to raise the windward wing; hence, dihedral contributes a stable roll due to sideslip. Since wing dihedral is so powerful in producing lateral stability, it is used as a "common denominator term" of the lateral stability contribution of other airplane components, such as rudder and wing sweep. In other words, the term "dihedral effect" is used when describing the effects of wing sweep and rudder on lateral stability and control.

A swept-wing design used on jet transport airplanes is beneficial for high-speed flight, since higher flight speeds may be obtained before components of speed perpendicular to the leading edge produce critical conditions on the wing. In other words, wing sweep will delay the onset of compressibility effects. This wing sweep also contributes to the dihedral effect. When the swept-wing airplane is placed in a sideslip, the wing into the wind experiences an increase in lift, since the effective sweep is less, and the wing away from the wind produces less lift, since the effective sweep is greater (Fig. 25). The amount of contribution, or dihedral effect, depends on the amount of sweepback and lift coefficient of the wing. The effect becomes greater with increasing lift coefficient and wing sweep. The lift coefficient will increase with increasing angle of attack up to the critical angle. This means that any sideslip results in more rolling moment on a swept-wing airplane than on a straight-wing airplane. Lateral controls on swept-wing airplanes are powerful enough to control large sideslip angles at operational speeds.

Rudder input produces sideslip and contributes to the dihedral effect. The effect is proportional to the angle of sideslip. (That is, roll increases with sideslip angle; therefore, roll increases with increasing rudder input.) Precise contol of roll angle using this technique is very difficult, and therefore, not recommended. The next section discusses this area in more detail. When an airplane is at a high angle of attack, aileron and

Figure 26
Wing Dihedral Angle



spoiler roll controls become less effective. At the stall angle of attack, the rudder is still effective; therefore, it can produce large sideslip angles, which in turn produces roll because of the dihedral effect.

2.5.5.4.3 Pilot-Commanded Sideslip

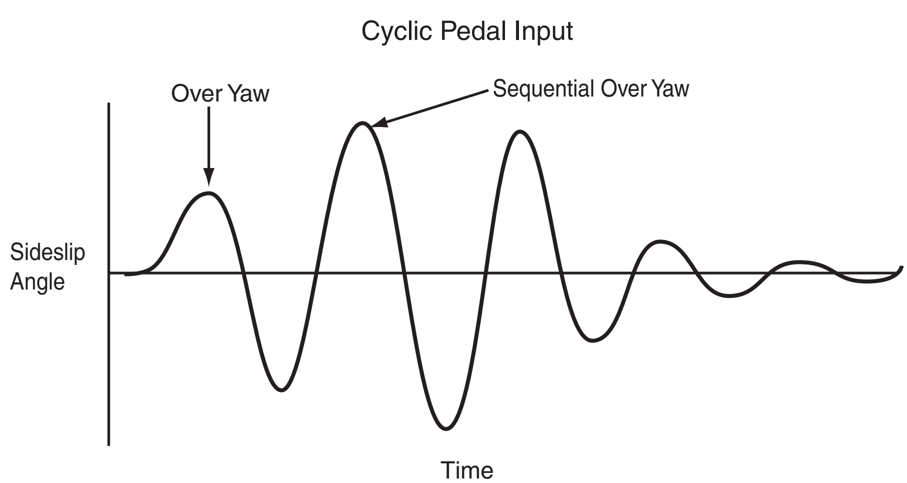
The rudders on modern jet transport airplanes are sized to counter the yawing moment associated with an engine failure at very low takeoff speeds and to ensure yaw control throughout the flight envelope, using up to maximum pedal input. This very powerful rudder is also capable of generating large sideslips. An inappropriate rudder input can produce a large sideslip angle, which will generate a large rolling moment that requires significant lateral control input to stop the airplane from rolling. The rudder should not normally be used to induce roll through sideslip because the transient sideslip can induce very rapid roll rates with significant time delay. The combination of rapid roll rates and time delay can startle the pilot, which in turn can cause the pilot to overreact in the opposite direction. The overreaction can induce abrupt yawing moments and violent out-of-phase roll rates, which can lead to successive cyclic rudder deflections, known as rudder reversals. *Large aggressive control reversals can lead to loads that can exceed structural design limits.* Figure 27 shows sideslip response to abrupt cyclic rudder input. Except in crosswind takeoff and landing, keeping the sideslip as close to zero as possible will ensure that the maximum amount of lateral control is available for maneuvering. On modern jet airplanes, the specific deflection combinations of ailerons and spoilers, with yaw dampers and turn coordinators, are usually designed to make adverse yaw undetectable to the pilot; hence the use of rudder is virtually eliminated during normal roll conditions. In any case, use of coordinated rudder in combination with ailerons/spoilers is to eliminate yaw and not to supplement or induce roll.

One way to determine the sideslip state of the airplane is to "feel" the lateral acceleration; it feels as if the pilot is being pushed out of the seat sideways. Another way is to examine the slip-skid indicator and keep the ball in the center. Pilots should develop a feel for the particular airplanes they fly and understand how to minimize sideslip angle through coordinated use of flight controls.

2.5.5.4.4 Crossover Speed

Crossover speed is a recently coined term that describes the lateral controllability of an airplane with the rudder at a fixed (up to maximum) deflection. It is the minimum speed (weight and configuration dependent) in a 1-g flight, where maximum aileron/spoiler input (against the stops) is reached and the wings are still level or at an angle to maintain directional control. Any additional rudder input or decrease in speed will result in an unstoppable roll into the direction of the deflected rudder or in an inability to maintain desired heading. Crossover speed is very similar in concept to V_{mca}, except that instead of being V_{mc} due to a thrust asymmetry, it is V_{mc} due to full rudder input. This crossover speed is weight and configuration dependent. However, it is also sensitive to angle of attack. With weight and configuration held constant, the crossover speed will increase with increased angle of attack and will decrease with decreased angle of attack. Thus, in an airplane upset due to rudder deflection with large and increasing bank angle and the nose rapidly falling below the horizon, the input of additional nose-up

Figure 27 Sideslip Response to Abrupt Cyclic Rudder Input



elevator with already maximum input of aileron/spoilers will only aggravate the situation. The correct action in this case is to unload the airplane to reduce the angle of attack, which will regain aileron/spoiler effectiveness and allow recovery. This action may not be intuitive and will result in a loss of altitude.

Note: The previous discussion refers to the aerodynamic effects associated with rudder input; however, similar aerodynamic effects are associated with other surfaces.

2.5.5.5 High-Speed, High-Altitude Characteristics

Modern commercial jet transport airplanes are designed to fly at altitudes from sea level to more than 40,000 ft. There are considerable changes in atmospheric characteristics that take place over that altitude range, and the airplane must accommodate those changes.

One item of interest to pilots is the air temperature as altitude changes. Up to the tropopause (36,089 ft in a standard atmosphere), the standard temperature decreases with altitude. Above the tropopause, the standard temperature remains relatively constant. This is important to pilots because the speed of sound in air is a function only of air temperature. Aerodynamic characteristics of lifting surfaces and entire airplanes are significantly affected by the ratio of the airspeed to the speed of sound. That ratio is represented as a Mach number. At high altitudes, large Mach numbers exist at relatively low calibrated airspeeds.

Pilots need to be aware of the Mach number and altitude effects on the stability and handling qualities of their airplanes. Many pilots know that maneuvering an airplane at traffic pattern altitudes “feels” different than maneuvering at the same calibrated airspeed at cruise altitude. As mentioned above, altitude and Mach number change the aerodynamic characteristics of the airplane – so it does “feel” and respond differently. As altitude increases (in a standard atmospheric model), air density decreases. When this occurs, natural aerodynamic damping decreases and the airplane becomes more responsive to control inputs. Higher Mach numbers may also adversely affect the stability of the airplane, causing undesirable characteristics to develop or worsen.

As Mach number increases, airflow over parts of the airplane begins to exceed the speed of sound. Shock waves associated with this local supersonic flow can interfere with the normally smooth flow over the lifting surfaces, causing local flow separation. Depending on the airplane, as this separation grows in magnitude with increasing Mach number, characteristics such as pitchup, pitchdown, or aerodynamic buffeting may occur. Transport category airplanes are certificated to be free from characteristics that would interfere with normal piloting in the normal flight envelope and to be safely controllable during inadvertent exceedances of the normal envelope, as discussed in Section 2.5.4, “Aerodynamic Flight Envelope.”

The point at which buffeting would be expected to occur is documented in the AFM. The Buffet Boundary or Cruise Maneuver Capability charts contain a wealth of information about the high-altitude characteristics of each airplane. A sample of such a chart is shown in Figure 28.

The chart provides speed margins to low-speed (stall-induced) and high-speed (shock-induced) buffet at 1 g, normal load factor or bank angle to buffet at a given Mach number, or altitude capability at a given Mach number and 1 g. The buffet boundaries of various airplanes can differ significantly in their shapes, and these differences contain valuable information for the pilot. Some airplanes have broad speed margins; some have abrupt high-speed buffet margins; some have narrow, “peaky” characteristics, as depicted notionally in Figure 29. Pilots should become familiar with the buffet boundaries. These boundaries let the pilot know how much maneuvering room is available, and they give clues for successful strategies should speed changes become rapid or attitude or flight path angles become large.

For example, the pilot of Airplane A in the figure has a broad speed range between high- and low-speed buffet onset at 1 g and the current altitude, with only a nominal g capability. Airplane B has by comparison a much smaller speed range between high- and low-speed buffet onset, but a generous g capability at the current Mach number. Airplane C is cruising much closer to the high-speed buffet boundary than the low-speed boundary, which lets the pilot know in which direction (slower) there is more margin available.

2.5.5.6 Stability

Positive static stability is defined as the initial tendency to return to an undisturbed state after a disturbance. This concept has been illustrated by the "ball in a cup" model (Fig. 30).

All transport airplanes demonstrate positive stability in at least some sense. The importance here is that the concept of stability can apply to a number of different parameters, all at the same time. Speed stability, the condition of an airplane returning to its initial trim airspeed after a disturbance, is familiar to most pilots. The same concept applies to Mach number. This stability can be independent of airspeed if, for example, the airplane crosses a cold front. When the outside air

Figure 28
Sample Buffet Boundary Chart

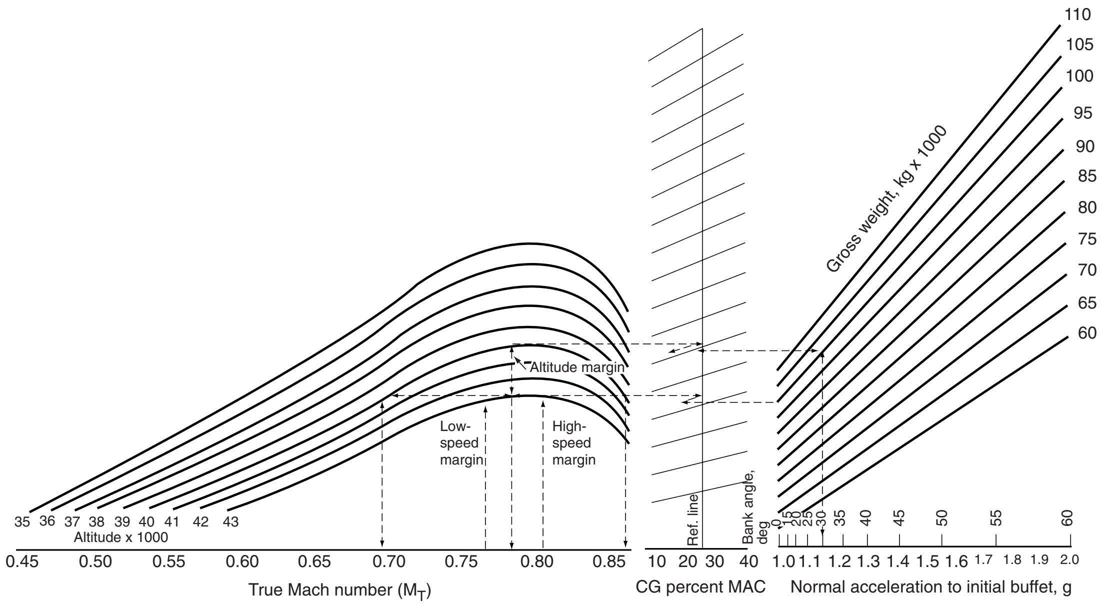


Figure 29
Notional Buffet Boundaries

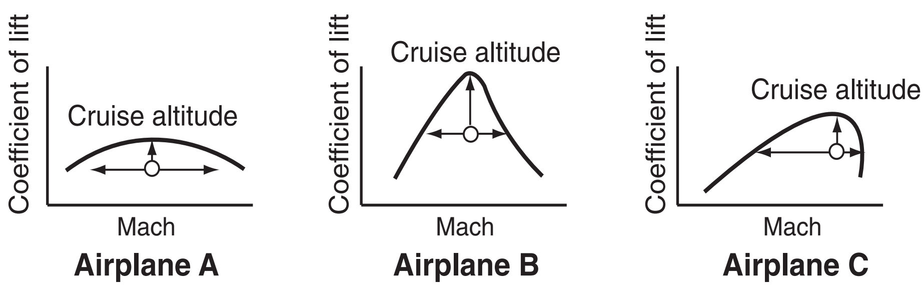
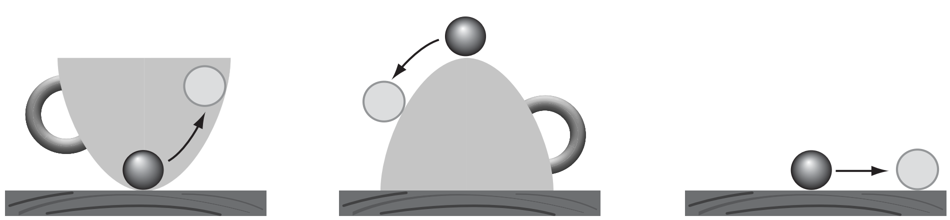


Figure 30
Static Stability



Stable
When ball is displaced, it returns to its original position.

Unstable
When ball is displaced, it accelerates from its original position.

Neutral
When ball is displaced, it neither returns, nor accelerates away—it just takes up a new position.

temperature changes, the Mach number changes, even though the indicated airspeed may not change. Airplanes that are "Mach stable" will tend to return to the original Mach number. Many jet transport airplanes incorporate Mach trim to provide this function. Similarly, commercial airplanes are stable with respect to load factor. When a gust or other disturbance generates a load factor, the airplane is certificated to be stable: it will return to its initial trimmed load factor (usually 1.0). This "maneuvering stability" requires a sustained pull force to remain at elevated load factors—as in a steep turn.

One important side effect of stability is that it allows for some unattended operation. If the pilot releases the controls for a short period of time, stability will help keep the airplane at the condition at which it was left.

Another important side effect of stability is that of tactile feedback to the pilot. On airplanes with static longitudinal stability, for example, if the pilot is holding a sustained pull force, the speed is probably slower than the last trim speed.

2.5.5.7 Maneuvering in Pitch

Movement about the lateral axis is called "pitch," as depicted in Figure 31.

Controlling pitching motions involves controlling aerodynamic and other moments about the center of gravity to modulate the angle of attack. Aside from the pitching moment effects of thrust when engines are offset from the center of gravity (discussed below), the pilot controls the pitching moments (and therefore the angle of attack) by means of the stabilizer and elevator. The horizontal stabilizer should be thought of as a trimming device, reducing the need to hold elevator deflection, while the elevator should be thought of as the primary maneuvering control. This is true because the horizontal stabilizer has only limited rate capability—it cannot change angle very quickly. Maneuvering, or active pilot modulation of the pitch controls, is usually accomplished by the elevator control, which is designed to move at much faster rates. To get a better understanding of how these components work together, the following discussion will examine the various components of pitching moment.

"Moments" have dimensions of force times distance. Pilots are familiar with moments from working weight and balance problems. In the case of pitching moment, we are concerned with moments about the center of gravity. So the pitching moment due to wing lift, for example, is the wing lift times the distance between the center of gravity and the center of the wing lift. Since weight acts through the center of gravity, there is no moment associated with it. In addition, there is a moment associated with the fact that the wing is usually cambered and with the fact that the fuselage is flying in the wing's flowfield. This wing-body moment does not have a force associated with it; it is a pure torque.

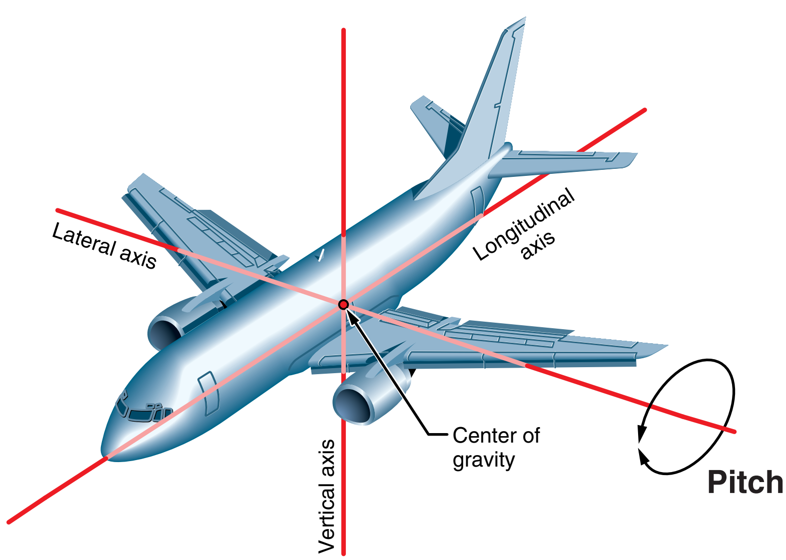


Figure 31
Reference Axis Definitions

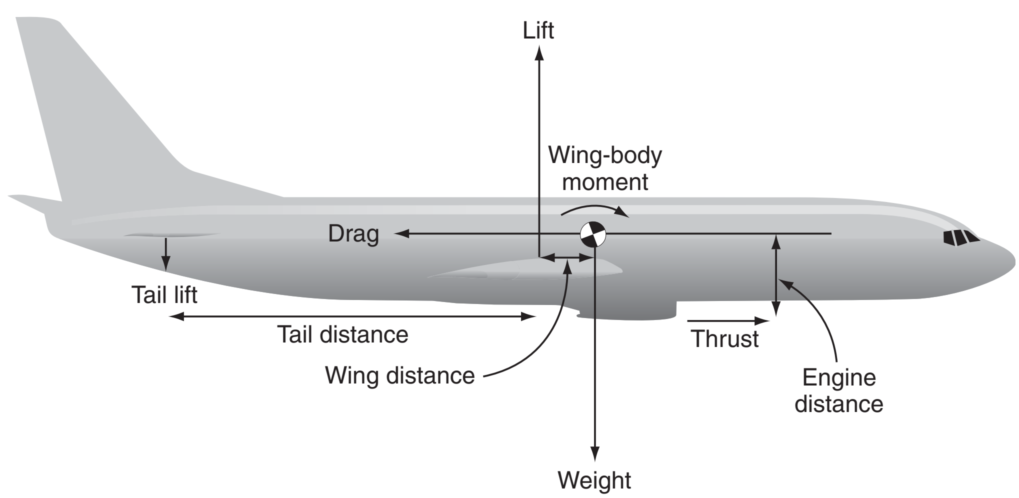
Figure 32 shows many of the important components of pitching moment about the center of gravity of an airplane. Weight acts through the center of gravity and always points toward the center of the Earth. In steady (unaccelerated) flight, the moments about the center of gravity, as well as the forces, are all balanced: the sum is zero. Since, in general, there is a pitching moment due to the wing and body and the lift is not generally aligned with the center of gravity—and the thrust of the engines is also offset from the center of gravity—there is usually some load on the horizontal tail required to balance the rest of the moments, and that load is generally in the downward direction, as shown in the figure.

Essentially, the pilot controls the amount of lift generated by the horizontal tail (by moving the elevator), which adjusts the angle of attack of the wing and therefore modulates the amount of lift that the wing generates. Similarly, since engines are rarely aligned with the center of gravity, changing the thrust will be accompanied by a change in the pitching moment around the center of gravity. The pilot then adjusts the lift on the tail (with the elevator) to again balance the pitching moments.

As long as the angle of attack is within unstalled limits and the airspeed is within limits, the aerodynamic controls will work to maneuver the airplane in the pitch axis as described. This is true regardless of the attitude of the airplane or the orientation of the weight vector.

Recall that the object of maneuvering the airplane is to manipulate the forces on the airplane in order to manage the energy state. The aerodynamic forces are a function of how the pilot manipulates the controls, changing angle of attack, for example. Similarly, the thrust forces are commanded by the pilot. The weight vector always points toward the center of the Earth. The orientation with respect to the airplane, though, is a function of the airplane attitude. The weight vector is a very powerful force. Recall that transport airplanes are certificated to 2.5 g. That means that the wing is capable of generating 2.5 times the airplane weight. In contrast, engine thrust is typically on the order of 0.3 times the airplane weight at takeoff weights.

Figure 32
Airplane Pitching Moments



$$(\text{Moment})_{\text{Tail}} + (\text{Moment})_{\text{Lift}} + (\text{Moment})_{\text{Thrust}} + (\text{Moment})_{\text{Wing-body}} = \text{Total pitching moment}$$

$$\left(\text{Tail lift} * \text{Tail distance}\right) + \left(\text{Wing lift} * \text{Wing distance}\right) + \left(\text{Thrust} * \text{Engine distance}\right) + (\text{Moment})_{\text{Wing-body}} = \text{Total pitching moment}$$

To get an appreciation for the magnitude of the weight vector and the importance of its orientation, consider the very simple example of Figure 33.

In a noseup pitch attitude, the component of the weight vector in the drag direction (parallel to the airplane longitudinal axis) equals the engine thrust at about 20 deg, noseup pitch attitude on a takeoff climb. Conversely, at nosedown pitch attitudes, the weight vector contributes to thrust. Since the magnitude of the weight vector is on the order of 3 times the available thrust, pilots need to be very careful about making large pitch attitude changes. When procedures call for a pitch attitude reduction to accelerate and clean up after takeoff, one aspect of that maneuver is getting rid of the weight component in the drag direction, allowing the airplane to gain speed.

2.5.5.8 Mechanics of Turning Flight

Recalling that Newton's laws dictate that an object in motion will continue in a straight line unless acted on by an external force, consider what is required to make an airplane turn. If a pilot wants to change the course of an airplane in flight, a force perpendicular to the flight path in the direction of the desired turn must first be generated. Usually this is accomplished by banking the airplane. This points the lift vector off to the side, generating a horizontal component of lift (Fig. 34). This is not the only way to generate a sideways-pointing force, but it is the typical method.

When the lift vector is tilted to generate the horizontal component, the vertical component gets smaller. Since the acceleration due to gravity still points toward the Earth, there is now an imbalance

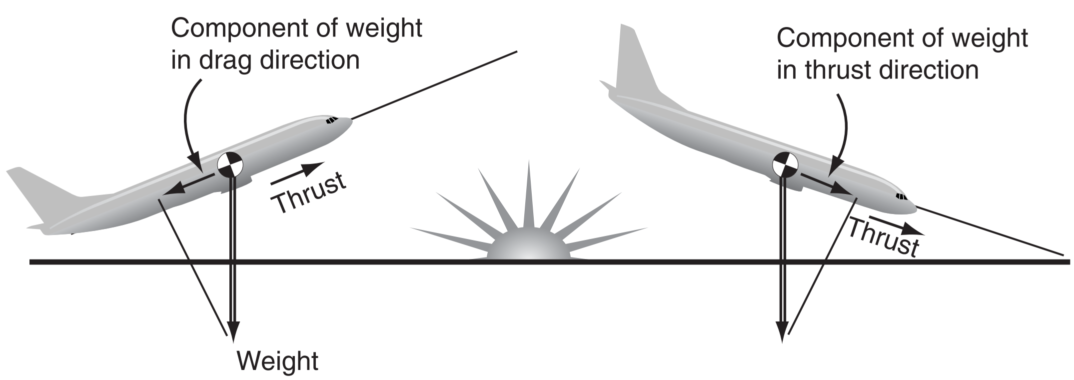


Figure 33
Contributions of Weight Vector

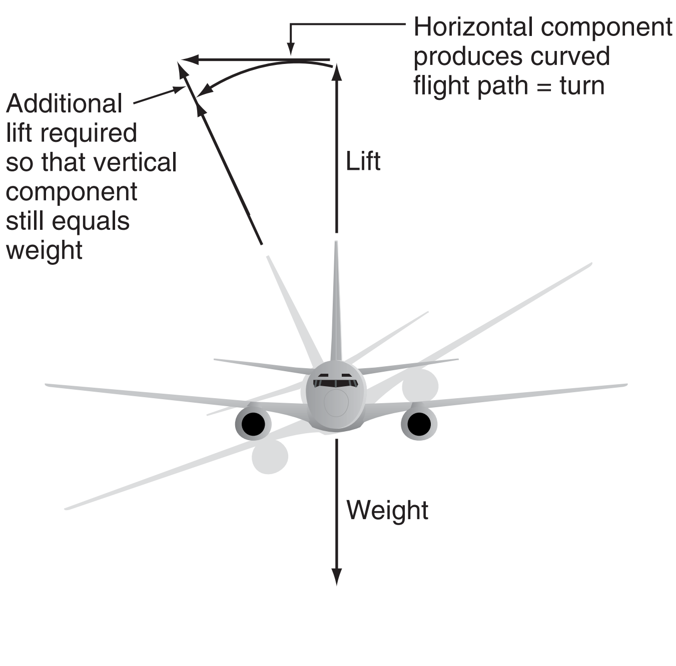


Figure 34
Mechanics of Turning Flight

in the vertical forces. Unless the lift vector is increased so that its vertical component equals the weight of the airplane, the airplane will begin to accelerate toward the Earth—it will begin to descend. To maintain altitude in a banked turn, the lift produced by the airplane must be more than the weight of the airplane, and the amount is a function of bank angle (Fig. 35).

All of this is well known, but it bears reiteration in the context of recovery from extreme airplane upsets. If the objective is to arrest a descent, maneuvering in pitch if the wings are not level will only cause a tighter turn and, depending on the bank angle, may not contribute significantly to generating a lift vector that points away from the ground. Indeed, Figure 35 indicates that to maintain level flight at bank angles beyond 66 deg requires a larger load factor than that for which transport airplanes are certificated.

In early training, many pilots are warned about the "Graveyard Spiral." The Graveyard Spiral maneuver is one in which the airplane is in a large bank angle and descending. The unknowing pilot fixates on the fact that airspeed is high and the airplane is descending. In an attempt to arrest both the speed and sinkrate, the pilot pulls on the column and applies up-elevator. However, at a large bank angle, the only effect of the up-elevator is to further tighten the turn. It is imperative to get the wings close to level before beginning any aggressive pitching maneuver. This orients the lift vector away from the gravity vector so that the forces acting on the airplane can be managed in a controlled way.

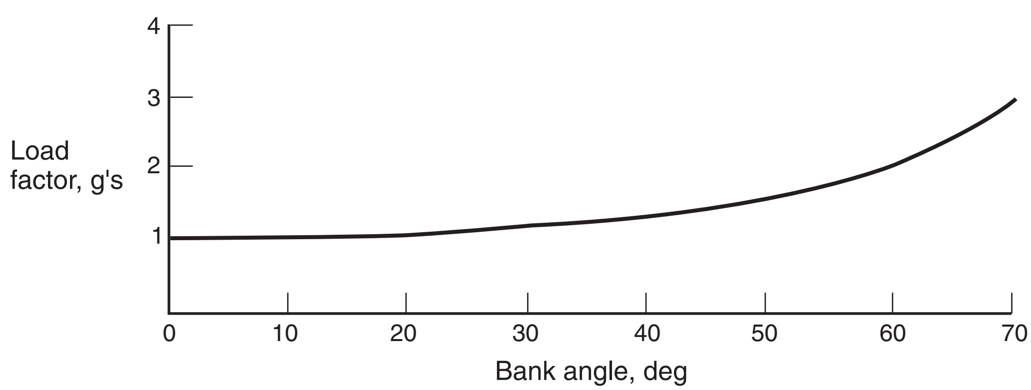
Knowledge of these relationships is useful in other situations as well. In the event that the load factor is increasing, excess lift is being generated, and the pilot does not want speed to decrease, bank angle can help to keep the flight path vector below the horizon, getting gravity to help prevent loss of airspeed. In this situation, the excess lift can be oriented toward the horizon and, in fact, modulated up and down to maintain airspeed.

2.5.5.9 Lateral Maneuvering

Motion about the longitudinal axis (Fig. 36) is called "roll." Modern jet transport airplanes use combinations of aileron and spoiler deflections as primary surfaces to generate rolling motion. These deflections are controlled by the stick or wheel, and they are designed to provide precise maneuvering capability. On modern jet airplanes, the specific deflection combinations of ailerons and spoilers, with yaw dampers and turn coordinators, are usually designed to make adverse yaw undetectable to the pilot; hence, the use of rudder is virtually eliminated during normal roll control. Supplementing normal roll control with rudder may induce uncoordinated turning moments, because the pilot inputs will be in addition to the aircraft system inputs, therefore, pilot rudder pedal inputs to augment turn coordination functions (if available) are not recommended.

As described in Section 2.5.5, "Aerodynamics," trailing edge control surfaces lose effectiveness in the downgoing direction at high angles of attack. Similarly, spoilers begin to lose effectiveness as the stall angle of attack is exceeded.

Figure 35
Bank Versus Load Factor (g's) for Level Flight



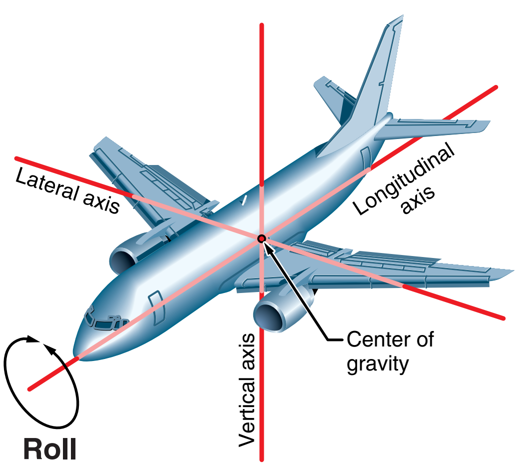
Transport airplanes are certificated to have positive unreversed lateral control up to a full aerodynamic stall. That is, during certification testing, the airplane has been shown to have the capability of producing and correcting roll up to the time the airplane is stalled. However, beyond the stall angle of attack, no generalizations can be made. ***For this reason it is critical to reduce the angle of attack at the first indication of stall so that control surface effectiveness is preserved.***

The apparent effectiveness of lateral control, that is, the time between the pilot input and when the airplane responds, is in part a function of the airplane's inertia about its longitudinal axis. Airplanes with very long wings, and, in particular, airplanes with engines distributed outboard along the wings, tend to have very much larger inertias than airplanes with engines located on the fuselage. This also applies to airplanes in which fuel is distributed along the wing span. Early in a flight with full wing (or tip) tanks, the moment of inertia about the longitudinal axis will be much larger than when those tanks are nearly empty. This greater inertia must be overcome by the rolling moment to produce a roll acceleration and resulting roll angle, and the effect is a "sluggish" initial response. As discussed before, airplanes of large mass and large inertia require that pilots be prepared for this longer response time and plan appropriately in maneuvering.

From a flight dynamics point of view, the greatest power of lateral control in maneuvering the airplane—in using available energy to maneuver the flight path—is to orient the lift vector. In particular, pilots need to be aware of their ability to orient the lift vector with respect to the gravity vector. Upright with wings level, the lift vector is opposed to the gravity vector, and vertical flight path is controlled by longitudinal control and thrust. Upright with wings not level, the lift vector is not aligned with gravity, and the flight path will be curved. In addition, if load factor is not increased beyond 1.0, that is, if lift on the wings is not greater than weight, the vertical flight path will become curved in the downward direction, and the airplane will begin to descend. Hypothetically, with the airplane inverted, lift and gravity point in the same direction: down. The vertical flight path will become curved and the airplane will accelerate toward the earth quite rapidly. In this case, the pilot must find a way to orient the lift vector away from gravity. In all cases, the pilot should ensure that the angle of attack is below the stall angle and roll to upright as rapidly as possible.

2.5.5.10 Directional Maneuvering

Motion about the vertical axis is called "yaw" (Fig. 37). The character of the motion about the vertical axis is determined by the balance of moments about the axis (around the center of gravity). The principal controller of aerodynamic moments about the vertical axis is the rudder, but it is not the only one. Moments about the vertical axis can be generated or affected by asymmetric thrust, or by asymmetric drag (generated by ailerons, spoilers, asymmetric flaps, and the like). These asymmetric moments may be desired (designed in) or undesired (perhaps the result of some failure).



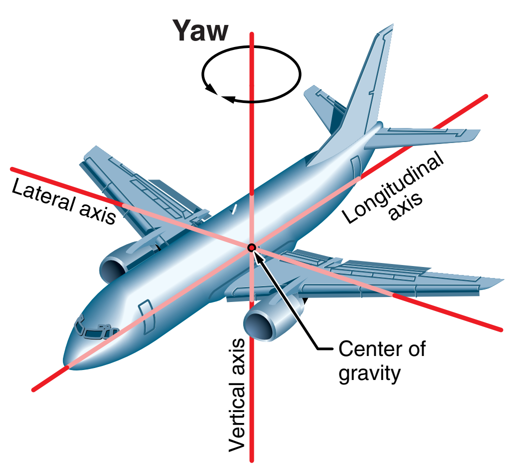


Figure 36 (Left) Roll Axis

Figure 37 Yaw Axis

Generally, the rudder is used to control yaw in a way that minimizes the angle of sideslip, that is, the angle between the airplane's longitudinal axis and the relative wind. For example, when an engine fails on takeoff, the object is to keep the airplane aligned with the runway by using rudder.

On modern jet transports with powerful engines located away from the centerline, an engine failure can result in very large yawing moments, and rudders are generally sized to be able to control those moments down to very low speeds. This means that the rudder is very powerful and has the capability to generate very large yawing moments. ***When the rest of the airplane is symmetric, for example, in a condition of no engine failure, very large yawing moments would result in very large sideslip angles and large structural loads should the pilot input full rudder when it is not needed.*** Pilots need to be aware of just how powerful the rudder is and the effect it can have when the rest of the airplane is symmetric.

Many modern airplanes limit the rudder authority in parts of the flight envelope in which large deflections are not required, for example, at high speeds. In this way, the supporting structure can be made lighter. Pilots also need to be aware of such "rudder limiting" systems and how they operate on airplanes. The implementation of the rudder limiting function and associated forces varies from model to model and between manufacturers. The force a pilot feels when pushing on the rudder pedals is analogous to that of a force generated by a spring. The more the pedal is displaced the greater the required force. All modern transport airplanes limit rudder deflection as airspeed increases. Engine out takeoff and crosswind landing requirements define the maximum rudder deflection (authority). As the airplane flies faster, less deflection is needed and rudder authority is therefore reduced.

Some airplanes have rudder limiters that reduce the rudder authority by changing the gearing between the rudder and the rudder pedals. As the airplane speeds up, the pilot must continue to fully deflect the rudder pedal to command full available rudder, even though the maximum available rudder deflection has been reduced. This means the pilot will have to apply the same force to the rudder pedal to achieve maximum *available* rudder deflection throughout the flight envelope. Figure 38a shows an example of this type of system.

On other models, as the airplane speeds up, the rudder authority is limited, but the gearing between the rudder and the rudder pedal does not change. Since rudder authority is limited, rudder pedal travel is also limited (i.e., full rudder pedal deflection is not required to get full available rudder deflection). Rudder pedal force is a function of rudder pedal deflection, so less force will be required to achieve maximum available rudder deflection as airspeed increases (Fig. 38b)

Figure 38a Example 1: Rudder Deflection and Force Requirements

V1			250kts			FL390 MMO		
Pedal force, lb	Pedal travel, in	Rudder deflection, deg	Pedal force, lb	Pedal travel, in	Rudder deflection, deg	Pedal force, lb	Pedal travel, in	Rudder deflection, deg
50	2.5	30	50	2.5	10	50	2.5	5

Figure 38b Example 2: Rudder Deflection and Force Requirements

V1			250kts			FL390 MMO		
Pedal force, lb	Pedal travel, in	Rudder deflection, deg	Pedal force, lb	Pedal travel, in	Rudder deflection, deg	Pedal force, lb	Pedal travel, in	Rudder deflection, deg
50	2.5	30	30	1.5	10	25	1.0	5

Airplanes do vary on the amount of rudder pedal force and displacement required to achieve maximum available rudder as airspeed changes. It is important that pilots understand their airplane's feel and response characteristics to flight control inputs. By understanding and becoming familiar with the airplane's characteristics, pilots will learn to apply the appropriate control input in response to various flight situations.

From a structural capability standpoint, the pilot does not have to be concerned about how fast or how hard to push the rudder pedal in one direction (from zero to full available pedal deflection) throughout the normal flight envelope. However, it is important to emphasize that limiters do not protect against the structural loads or excessive sideslip angles that can be generated from rapid full deflection flight control reversals.

There are a few cases, however, when it is necessary to generate sideslip. One of the most common is the crosswind landing. In the slip-to-a-landing technique, simultaneous use of rudder and aileron/spoiler aligns the airplane with the runway centerline and at the same time keeps the airplane from drifting downwind. The airplane is flying "sideways" and the pilot feels the lateral acceleration.

Static directional stability is a measure of the tendency of an airplane to weathervane into the free stream airmass. The vertical fin and distribution of flat plate area aft of the CG tend to reduce sideslip and add to good directional stability. All conventional airplanes require positive static directional stability. In simple terms, an airplane with good directional stability always wants to point directly into the relative wind—zero sideslip. As directional stability increases, the speed at which the aircraft returns to zero sideslip after being disturbed increases (higher frequency). In order to minimize overshoots in sideslip, the damping in the directional axis must be increased as the directional stability is increased. An undesirable characteristic can develop when the directional damping is not adequate enough to prevent overshoots in sideslip. A phenomenon known as "Dutch roll" (based on the similarity with the motions of high-speed ice skaters) can occur. A Dutch roll occurs when yaw rates produce sideslips, which produce roll rates. If the sideslips are not adequately damped, the aircraft nose will swing back and forth with respect to the relative wind, and the aircraft will roll right and left due to the dihedral effect (the wingsweep results in asymmetric lift, depending on the relative wind). Airplanes designed to fly at higher Mach numbers have more wingsweep to control the critical Mach number (the speed at which shock waves begin to form on the wing). As wingsweep increases, the dihedral effect increases, and if the airplane is not adequately damped in the directional axis, a Dutch roll might occur if the airplane is upset directionally. Yaw dampers were designed to minimize yaw rates, which result in sideslip rates, and are very effective in modern transports in damping the Dutch roll. However, some transport airplanes have a neutral or slightly divergent Dutch roll if the yaw damper is off or inoperative. Conventional airplanes exhibit more of a Dutch roll tendency at higher altitude (less damping) and higher speed (more directional stability). Therefore, if a pilot encounters a Dutch roll condition, every effort should be made to "slow down and go down." With a properly functioning yaw damper, Dutch rolls will not occur in modern transport aircraft. Transport airplanes are certificated to demonstrate positively damped Dutch roll oscillations. The rudder should not be used to complement the yaw damper system. If the yaw damper system is inoperative, the rudder should not be used to dampen Dutch roll. Refer to your aircraft's non-normal section for procedures to deal with yaw damper failure.

The installed systems that can drive the rudder surface are typically designed in a hierarchical manner. For example, the yaw damper typically has authority to move the rudder in only a limited deflection range. Rudder trim, selectable by the pilot, has authority to command much larger rudder deflections that may be needed for engine failure. In most cases, the pilot, with manual control over rudder deflection, is the most powerful element in the system. The pilot can command deflection to the limits of the system, which may be surface stops, actuator force limits, or any others that may be installed (e.g., rudder ratio changers).

Precise roll control using rudder is difficult and therefore not recommended. The use of up to full rudder for control of engine failures and crosswind takeoffs and landings is what the system was designed to do. Airplanes do vary on the amount of rudder pedal force and displacement required to achieve maximum available rudder as airspeed changes. It is important that pilots understand their airplane's feel and response characteristics to flight

control inputs. By understanding and becoming familiar with the airplane's response characteristics, pilots will learn to apply the appropriate control input in response to various flight situations. Transport pilots should be aware that certain prior experience or training in military, GA, or other nontransport aircraft that emphasizes use of rudder input as a means to maneuver in roll typically does not apply to transport aircraft or operations. When normal means of roll control have been unsuccessful, careful rudder input in the direction of the desired roll should be considered to induce or augment a rolling maneuver or to provide the desired bank angle. A rudder input is never the preferred initial response for events such as a wake vortex encounter or windshear encounter, or to reduce the bank angle preceding an imminent stall recovery.

2.5.5.11 Flight at Extremely Low Airspeeds

Stall speed is discussed in Section 2.5.5.1. It is possible for the airplane to be flown at speeds below the defined stall speed. This regime is outside the certified flight envelope. At extremely low airspeeds, there are several important effects for the pilot to know.

Recall from the discussion of aerodynamics that the aerodynamic lift that is generated by wings and tails depends on both the angle of attack and the velocity of the air moving over the surfaces. Angle of attack alone determines whether the surface is stalled. At very low airspeeds, even far below the strictly defined stall speed, an unstalled surface (one at a low angle of attack) will produce lift. However, the magnitude of the lift force will probably be very small. For a surface in this condition, the lift generated will not be enough to support the weight of the airplane. In the case of the lift generated by the tail, at very low airspeeds, it may not be great enough to trim the airplane, that is, to keep it from pitching.

With small aerodynamic forces acting on the airplane, and gravity still pulling towards the earth, the trajectory will be largely ballistic. It may be difficult to command a change in attitude until gravity produces enough airspeed to generate sufficient lift—and that is only possible at angles of attack below the stall angle. For this reason, if airspeed is decreasing rapidly it is very important to reduce angle of attack and use whatever aerodynamic forces are available to orient the airplane so that a recovery may be made when sufficient forces are available.

When thrust is considered, the situation becomes only slightly more complicated. With engines offset from the center of gravity, thrust produces both forces and moments. In fact, as airspeed decreases, engine thrust generally increases for a given throttle setting. With engines below the center of gravity, there will be a noseup moment generated by engine thrust. Especially at high power settings, this may contribute to even higher noseup attitudes and even lower airspeeds. Pilots should be aware that as aerodynamic control effectiveness diminishes with lower airspeeds, the forces and moments available from thrust become more evident, and until the aerodynamic control surfaces become effective, the trajectory will depend largely on inertia and thrust effects.

2.5.5.12 Flight at Extremely High Speeds

Inadvertent excursions into extremely high speeds, either Mach number or airspeed, should be treated very seriously. As noted in the section on high-speed, high-altitude aerodynamics (Sec. 2.5.5.5), flight at very high Mach numbers puts the airplane in a region of reduced maneuvering envelope (closer to buffet boundaries). Many operators opt to fly at very high altitudes, because of air traffic control (ATC) and the greater efficiencies afforded there. But operation very close to buffet-limiting altitudes restricts the range of Mach numbers and load factors available for maneuvering. During certification, all transport airplanes have been shown to exhibit safe operating characteristics with inadvertent exceedances of Mach envelopes. These exceedances may be caused by horizontal gusts, penetration of jet stream or cold fronts, inadvertent control movements, leveling off from climb, descent from Mach-limiting to airspeed-limiting altitudes, gust upsets, and passenger movement. This means that the controls will operate normally and airplane responses are positive and predictable for these conditions. Pilots need to be aware that the maneuvering envelope is small and that prudent corrective action is necessary to avoid exceeding the other end of the envelope during recovery. Pilots should become very familiar with the high-speed buffet boundaries of their airplane and the combinations of weights and altitudes at which they operate.

Flight in the high-airspeed regime brings with it an additional consideration of very high control power. At speeds higher than maneuver speed V_A

(Fig. 14), a ***single*** very large deflection in pitch or roll has the potential to generate structural damage or failure. A single full-scale deflection in yaw is acceptable to at least maximum operating speed. At any speed, large aggressive control deflection ***reversals*** can lead to loads that can exceed structural design limits. It is worth a reminder that certification flight tests involve control input in a ***single*** axis and ***single*** direction. Control ***reversals*** will amplify the loads on the aircraft structures, while possibly leading to overcontrol (and even loss of control) situations.

In either the Mach or airspeed regime, if speed is excessive, the first priority should be to reduce speed to within the normal envelope. Many tools are available for this, including orienting the lift vector away from the gravity vector; adding load factor, which increases drag; reducing thrust; and adding drag by means of the speedbrakes. As demonstrated in Section 2.5.5.8, “Mechanics of Turning Flight,” the single most powerful force the pilot has available is the wing lift force. The second largest force acting on the airplane is the weight vector. Getting the airplane maneuvered so that the lift vector points in the desired direction should be the first priority, and it is the first step toward managing the energy available in the airplane.

2.5.5.13 Defensive, Aggressive Maneuvers

The result of events of September 11, 2001, have prompted a portion of the Flight Operations community to consider the use of the aircraft as a defensive weapon to prevent or slow down a hijacker’s access to a transport category aircraft flight deck. Due to the high probability of injury to passengers/crew and the likelihood of an upset and loss of control or damage to the aircraft, it is not recommended other than as a last resort. Even then, random unplanned maneuvers outside the manufacturer’s recommendations must be avoided.

2.6 Recovery From Airplane Upsets

Previous sections of this training aid review the causes of airplane upsets to emphasize the principle of avoiding airplane upsets. Basic aerodynamic information indicates how and why large, swept-wing airplanes fly. That information provides the foundation of knowledge necessary for recovering an airplane that has been upset. This section highlights several issues associated with airplane upset recovery and presents basic recommended airplane-recovery techniques for pilots. There are infinite potential situations that pilots can experience while flying an airplane. The techniques that are presented in this section are applicable for most situations. It must be emphasized that a developing upset will define how prompt or aggressive the required control inputs will be to recover from the event. In all cases the pilot response to an upset must be appropriate to arrest and recover the condition. Up to full-scale control deflections may be necessary; however, initiating recovery with arbitrary full-scale control deflections could actually aggravate the situation. An excessive or inappropriate control input that overshoots the desired response can startle the pilot and cause one upset to lead to another.

An overview of actions to take to recover from an upset would encompass three basic activities: Manage the energy, arrest the flight path divergence, and recover to a stabilized flight path. These three activities should be part of every recovery from an upset and provide an overview of actions taken.

2.6.1 Situation Awareness of an Airplane Upset

In most cases effective situational awareness will avoid an upset from developing in the first place. However, it is important that the first actions for recovering from an airplane upset be correct and timely. Exaggerated control inputs through reflex responses must be avoided. It is worth repeating that inappropriate control inputs during one upset recovery can lead to a different upset situation. ***Troubleshooting the cause of the upset is secondary to initiating the recovery. However, the pilot still must recognize and confirm the situation before a recovery can be initiated. Regaining and then maintaining control of the airplane is paramount.*** Communication between crew members will assist in the recovery actions. At the first indication of an unusual occurrence, the pilot should announce what is being observed.

It is necessary to use the primary flight instruments and airplane performance instruments when analyzing the upset situation. Visual meteorological conditions may allow the use of references outside the airplane. However, it can be difficult or impossible to see the horizon because in most large commercial airplanes, the field of view is restricted due to window geometry and overhead panel placement. For example, the field of view from an airplane that exceeds a 25-deg, noseup

attitude probably is limited to a view of the sky. Conversely, the field of view is restricted to the ground for a nose-down pitch attitude that exceeds 10 deg. In addition, pilots must be prepared to analyze the situation during darkness and when instrument meteorological conditions (IMC) exist. Therefore, the attitude direction indicator (ADI) is used as a primary reference for recovery. Compare the ADI information with performance instrument indications before initiating recovery. For a nose-low upset, normally the airspeed is increasing, altitude is decreasing, and the vertical speed indicator (VSI) indicates a descent. For a nose-high upset, the airspeed normally is decreasing, altitude is increasing, and the VSI indicates a climb. Cross-check other attitude sources, for example, the Standby Attitude Indicator and the pilot not flying (PNF) instruments.

Pitch attitude is determined from the ADI pitch reference scales (sometimes referred to as pitch ladder bars). Most modern airplanes also use colors (blue for sky, brown for ground) or ground perspective lines to assist in determining whether the airplane pitch is above or below the horizon. Even in extreme attitudes, some portion of the sky or ground indications is usually present to assist the pilot in analyzing the situation.

The bank indicator on the ADI should be used to determine the airplane bank.

The situation analysis process is to

a. Communicate with crew members.
b. Locate the bank indicator.
c. Determine pitch attitude.
d. Confirm attitude by reference to other indicators.
e. Assess the energy (refer to Section 2.5.2).

Recovery techniques presented later in this section include the phrase, "Recognize and confirm the situation." This situation analysis process is used to accomplish that technique.

2.6.2 Miscellaneous Issues Associated With Upset Recovery

There are issues associated with differences between simulator training and aircraft recoveries. A simulator can provide the basic fundamentals for upset recovery, but some realities such as positive or negative g's, startle factor, and environmental conditions are difficult or impossible to replicate. These limitations in simulation add a degree of complexity to recovery from an actual aircraft upset because the encounter can be significantly different from that experienced during simulator training. Therefore memory checklists or procedural responses performed in training may not be repeatable during an actual upset situation. The limitations of simulators at the edges of the flight envelope can also cause fidelity issues because the simulator recovery may or may not have the same response characteristics as the aircraft being flown. However, provided the alpha and beta limits are not exceeded, the initial motion responses and instrument indications of the simulator should replicate airplane responses. The reaction of the simulator is based on given parameters (CG, weight, speeds, etc.). An actual encounter at greatly different parameters than those practiced in the simulator may result in a different aircraft response. For example, flight controls are more effective at 250kn than at 150kn. These same realities exist for thrust asymmetry, wind shear, stall recovery, and the like.

2.6.2.1 Startle Factor

It has already been stated that airplane upsets do not occur very often and that there are multiple causes for these unpredictable events. Therefore, pilots are usually surprised or startled when an upset occurs. There can be a tendency for pilots to react before analyzing what is happening or to fixate on one indication and fail to properly diagnose the situation. Proper and sufficient training is the best solution for overcoming the startle factor. The pilot must overcome the surprise and quickly shift into analysis of what the airplane is doing and then implement the proper recovery. ***Gain control of the airplane and then determine and eliminate the cause of the upset.***

2.6.2.2 Negative G Force

Airline pilots are normally uncomfortable with aggressively unloading the g forces on a large passenger airplane. They habitually work hard at being very smooth with the controls and keeping a positive 1-g force to ensure flight attendant and passenger comfort and safety. Therefore, they must overcome this inhibition when faced with having to quickly and sometimes aggressively unload the airplane to less than 1 g by pushing down elevator.

Note: It should not normally be necessary to obtain less than 0 g.

While flight simulators can replicate normal flight profiles, most simulators cannot replicate sustained negative-g forces. Pilots must anticipate a significantly different cockpit environment during less-than-1-g situations. They may be floating up against the seat belts and shoulder harnesses. It may be difficult to reach or use rudder pedals if they are not properly adjusted. Unsecured items such as flight kits, approach plates, or lunch trays may be flying around the cockpit. These are things that the pilot must be prepared for when recovering from an upset that involves forces less than 1-g flight.

2.6.2.3 Use of Full Control Inputs

Utilizing full flight control authority is not a part of routine airline flying. Pilots must be prepared to use full flight control authority if the situation warrants it. In normal conditions, flight control inputs become more effective with increased speed/ reduced angle of attack. Conversely, at speeds approaching the critical angle of attack, larger control inputs are needed for given aircraft reactions. Moreover, during certain abnormal situations (partial high lift devices, thrust reverser in flight) large or full-scale control inputs may be required. Attitude and flight path changes can be very rapid during an upset and in responding to these sorts of upset conditions, large control inputs may be necessary. It is important to guard against control reversals. There is no situation that will require rapid full-scale control deflections from one side to the other.

2.6.2.4 Counter-Intuitive Factors

Pilots are routinely trained to recover from *approach* to stalls. The recovery usually requires an increase in thrust and a relatively small reduction in pitch attitude. Therefore, it may be counter-intuitive to use greater unloading control forces or to reduce thrust when recovering from a high angle of attack, especially at lower altitudes. If the airplane is stalled while already in a nosedown attitude, the pilot must still push the nose down in order to reduce the angle of attack. ***Altitude cannot be maintained and should be of secondary importance.***

2.6.2.5 Previous Training in Nonsimilar Airplanes

Aerodynamic principles do not change, but airplane design creates different flight characteristics. Therefore, training and experience gained in one model or type of airplane may or may not be transferable to another. ***For example, the handling characteristics of a fighter-type airplane cannot be assumed to be similar to those of a large, commercial, swept-wing airplane.*** Airplanes with electronic flight control systems may provide protection against entering into many upset situations. These systems also assist the airplane to return to normal flight, if necessary. However, when fly-by-wire airplanes operate in a degraded mode, flight control inputs and the responses can be similar to non fly-by-wire airplanes.

2.6.2.6 Potential Effects on Engines

Some extreme airplane upset situations may affect engine performance. Large angles of attack can reduce the flow of air into the engine and result in engine surges or compressor stalls. Additionally, large and rapid changes in sideslip angles can create excessive internal engine side loads, which may damage an engine.

2.6.2.7 Post Upset Conditions

Pilots and operations managers need to consider the physiological and psychological aspects that exist after recovering from an upset. Initially, there will be a tendency to overcontrol the airplane because of the large deviations and control inputs previously experienced. Pilots need to dampen out these excursions if they happen. There could be confusion on the flight deck as to what exactly happened to cause the original upset. Care should be taken not to take action that could cause a repeat of the previous upset or let the airplane progress into a different kind of upset. Pilots may not be able to recall the forces experienced or the extent of the maneuvers performed to any great detail. If large g-forces are experienced, then an aircraft inspection would be appropriate. Pilots and operations managers should consider all the aspects of the upset recovery to determine if continued flight or crew changes are required.

2.6.3 Airplane Upset Recovery Techniques

An Airplane Upset Recovery Team comprising representatives from airlines, pilot associations, airplane manufacturers, and government aviation and regulatory agencies developed the techniques presented in this training aid. These techniques are not necessarily procedural. Use of both primary and secondary flight controls to effect the recovery from an upset are discussed. Individual operators must address procedural application within their own airplane fleet structure. The Airplane Upset Recovery Team strongly recommends that techniques for initial recovery emphasize the use of primary flight controls (aileron, elevator, and rudder). Secondary control devices, such as stabilizer trim, thrust, and speed-brakes, may be considered incrementally to supplement primary flight control inputs. Flight crews need to manage the energy, arrest the flight path divergence, and recover to a stabilized flight path.

For instructional purposes, several different airplane upset situations are discussed. These include the following:

- Nose high, wings level.
- Nose low, wings level.
  - Low airspeed.
  - High airspeed.
- High bank angles.
  - Nose high.
  - Nose low.

This provides the basis for relating the aerodynamic information and techniques to specific situations. ***At the conclusion of this recovery techniques section, recommended recovery techniques are summarized into two basic airplane upset situations: nose high and nose low.*** Consolidation of recovery techniques into these two situations is done for simplification and ease of retention.

◆ Following several situations, where appropriate, abbreviated techniques used for recovery are indicated by the solid diamond shown here.

Airplanes that are designed with electronic flight control systems, commonly referred to as “fly-by-wire” airplanes, have features that should minimize the possibility that the airplane would enter into an upset and assist the pilot in recovery, if it becomes necessary. But, when fly-by-wire airplanes are in the degraded flight control mode, the recovery techniques and aerodynamic principles discussed in this training aid are appropriate. Some environmental conditions can upset any airplane. But the basic principles of recognition and recovery techniques still apply, independent of flight control architecture.

Airplane autopilots and autothrottles are intended to be used when the airplane is within its normal flight regime. ***When an airplane has been upset, the autopilot and autothrottle must be disconnected as a prelude to initiating recovery techniques.*** Situational analysis of the energy state of the aircraft is also required. This analysis assesses the energy and trend. This includes but is not limited to altitude, airspeed, attitude, load factor, power setting, position of flight controls, position of drag and high-lift devices, and the rate of change. This analysis may cause the crew to make appropriate changes, such as use of speed brakes or lowering the landing gear for drag as necessary to aid in the recovery. In other words, manage the energy.

2.6.3.1 Stall

The recovery techniques assume the airplane is not stalled. An airplane is stalled when the angle of attack is beyond the stalling angle. A stall is characterized by any of, or a combination of, the following:

a. Buffeting, which could be heavy at times.
b. A lack of pitch authority.
c. A lack of roll control.
d. Inability to arrest descent rate.

These characteristics are usually accompanied by a continuous stall warning.

A stall must not be confused with a stall warning that occurs before the stall and warns of an approaching stall. Recovery from an approach to stall warning is not the same as recovering from a stall. An approach to stall is a controlled flight maneuver. A stall is an out-of-control condition, but it is recoverable. ***To recover from the stall, angle of attack must be reduced below the stalling angle—apply nosedown pitch control and maintain it until stall recovery.*** Under certain conditions, on airplanes with underwing-mounted engines, it may be necessary to reduce thrust to prevent the angle of attack from continuing to increase. ***If the airplane is stalled, it is necessary to first recover from the stalled condition before initiating upset recovery techniques.***

2.6.3.2 Nose-High, Wings-Level Recovery Techniques

Situation: Pitch attitude unintentionally more than 25 deg, nose high, and increasing.

Airspeed decreasing rapidly.

Ability to maneuver decreasing.

Start by disengaging the autopilot and autothrottle and recognize and confirm the situation. Next, apply nosedown elevator to achieve a nosedown pitch rate. This may require as much as full nosedown input. If a sustained column force is required to obtain the desired response, consider trimming off some of the control force. However, it may be difficult to know how much trim should be used; therefore, care must be taken to avoid using too much trim. Do not fly the airplane using pitch trim, and stop trimming nosedown as the required elevator force lessens. If at this point the pitch rate is not immediately under control, there are several additional techniques that may be tried. The use of these techniques depends on the circumstances of the situation and the airplane control characteristics.

Pitch may be controlled by rolling the airplane to a bank angle that starts the nose down. The angle of bank should not normally exceed approximately 60 deg. Continuous nosedown elevator pressure will keep the wing angle of attack as low as possible, which will make the normal roll controls effective. With airspeed as low as the onset of the stick shaker, or lower, up to full deflection of the ailerons and spoilers can be used. The rolling maneuver changes the pitch rate into a turning maneuver, allowing the pitch to decrease. (Refer to Fig. 33.) In most situations, these techniques should be enough to recover the airplane from the nose-high, wings-level upset. However, other techniques may also be used to achieve a nosedown pitch rate.

If altitude permits, flight tests have shown that an effective method for getting a nosedown pitch rate is to reduce the power on underwing-mounted engines. (Refer to Sec. 2.5.5.11, "Flight at Extremely Low Airspeeds.") This reduces the upward pitch moment. In fact, in some situations for some airplane models, it may be necessary to reduce thrust to prevent the angle of attack from continuing to increase. This usually results in the nose lowering at higher speeds and a milder pitchdown. This makes it easier to recover to level flight.

If control provided by the ailerons and spoilers is ineffective, rudder input may be required to induce a rolling maneuver for recovery. ***Only a small amount of rudder input is needed. Too much rudder applied too quickly or held too long may result in loss of lateral and directional control.*** Caution must be used when applying rudder because of the low-energy situation. (Refer to Sec. 2.5.5.10, "Directional Maneuvering.")

To complete the recovery, roll to wings level, if necessary, as the nose approaches the horizon. Recover to slightly nose-low attitude to reduce the potential for entering another upset. Check airspeed, and adjust thrust and pitch as necessary.

Nose-high, wings-level recovery:
- ◆ Recognize and confirm the situation.
- ◆ Disengage autopilot and autothrottle.
- ◆ Apply as much as full nosedown elevator.
- ◆ Use appropriate techniques:
  - Roll to obtain a nosedown pitch rate.
  - Reduce thrust (underwing-mounted engines).
- ◆ Complete the recovery:
  - Approaching horizon, roll to wings level.
  - Check airspeed, adjust thrust.
  - Establish pitch attitude.

2.6.3.3 Nose-Low, Wings-Level Recovery Techniques

Situation: Pitch attitude unintentionally more than 10 deg, nose low.

Airspeed low.

Recognize and confirm the situation. Disengage the autopilot and autothrottle. Even in a nose-low, low-speed situation, the airplane may be stalled at a relatively low pitch. It is necessary to recover from the stall first. This may require nosedown elevator, which may not be intuitive. Once recovered from the stall, apply thrust. The nose must be returned to the desired pitch by applying noseup elevator. Avoid a secondary stall, as indicated by stall warning or airplane buffet. Airplane limitations of g forces and airspeed must be respected. (Refer to Sec. 2.5.2, "Energy States.")

Situation: Pitch attitude unintentionally more than 10 deg, nose low.

Airspeed high.

Recognize and confirm the situation. Disengage the autopilot and autothrottle. Apply noseup elevator. Then it may be necessary to cautiously apply stabilizer trim to assist in obtaining the desired noseup pitch rate. Stabilizer trim may be necessary for extreme out-of-trim conditions. Reduce thrust, and, if required, extend speedbrakes. The recovery is completed by establishing a pitch, thrust, and airplane configuration that corresponds to the desired airspeed. (Refer to Sec. 2.5.2, "Energy States.") Remember that a very clean airplane can quickly exceed its limits. When applying noseup elevator, there are several factors that the pilot should consider. Obviously, it is necessary to avoid impact with the terrain. Do not enter into an accelerated stall by exceeding the stall angle of attack. Airplane limitations of g forces and airspeed should also be respected.

Nose-low, wings-level recovery:

- ◆ Recognize and confirm the situation.
- ◆ Disengage autopilot and autothrottle.
- ◆ Recover from stall, if necessary.
- ◆ Recover to level flight:
  - Apply noseup elevator.
  - Apply stabilizer trim, if necessary.
  - Adjust thrust and drag, as necessary.

2.6.3.4 High-Bank-Angle Recovery Techniques

Bank angles can exceed 90 deg. In high-bank situations, the primary objective is to roll the airplane in the shortest direction to near wings level. However, if the airplane is stalled, it is first necessary to recover from the stall.

Situation: Bank angle greater than 45 deg.

Pitch attitude greater than 25 deg, nose high.

Airspeed decreasing.

A nose-high, high-angle-of-bank attitude requires deliberate flight control inputs. A large bank angle is helpful in reducing excessively high pitch attitudes. (Refer to Sec. 2.5.5.8, "Mechanics of Turning Flight.") Recognize and confirm the situation. Disengage the autopilot and autothrottle. Unload (reduce the angle of attack) and adjust the bank angle, not to exceed 60 deg, to achieve a nosedown pitch rate. Maintain awareness of energy management and airplane roll rate. To complete the recovery, roll to wings level as the nose approaches the horizon. Recover to a slightly nose-low attitude. Check airspeed and adjust thrust and pitch as necessary.

Situation: Bank angle greater than 45 deg.

Pitch attitude lower than 10 deg, nose low.

Airspeed increasing.

A nose-low, high-angle-of-bank attitude requires prompt action, because altitude is rapidly being exchanged for airspeed. Even if the airplane is at an altitude where ground impact is not an immediate concern, airspeed can rapidly increase beyond airplane design limits. Recognize and confirm the situation. Disengage the autopilot and autothrottle. Simultaneous application of roll and adjustment of thrust may be necessary. ***It may be necessary to unload the airplane by decreasing backpressure to improve roll effectiveness. If the airplane has exceeded 90 deg of bank, it may feel like "pushing" in order to unload. It is necessary to unload to improve roll control and to prevent pointing the lift vector towards the ground.*** Full aileron and spoiler input may be necessary to smoothly establish a recovery roll rate toward the nearest horizon. It is important that positive g force not be increased or that nose-up elevator or stabilizer trim be used until the airplane approaches wings level. If the application of full lateral control (ailerons and spoilers) is not satisfactory, it may be necessary to apply rudder in the direction of the desired roll. ***Only a small amount of rudder input is needed. Too much rudder applied too quickly or held too long may result in loss of lateral and directional control and cause structural damage.*** As the wings approach level, extend speedbrakes, if required. Complete the recovery by establishing a pitch, thrust, and airplane drag device configuration that corresponds to the desired airspeed. In large transport-category airplanes, do not attempt to roll through (add pro-roll controls) during an upset in order to achieve wings level more quickly. Roll in the shortest direction to wings level.

2.6.3.5 Consolidated Summary of Airplane Recovery Techniques

These summaries incorporate high-bank-angle techniques.

Nose-high recovery:

- Recognize and confirm the situation.
- Disengage autopilot and autothrottle.
- Apply as much as full nosedown elevator.
- Use appropriate techniques:
  - Roll (adjust bank angle) to obtain a nosedown pitch rate.
  - Reduce thrust (underwing-mounted engines).
- Complete the recovery:
  - Approaching the horizon, roll to wings level.
  - Check airspeed, adjust thrust.
  - Establish pitch attitude.

Nose-low recovery:

- Recognize and confirm the situation.
- Disengage autopilot and autothrottle.
- Recover from stall, if necessary.
- Roll in the shortest direction to wings level—bank angle more than 90 deg, unload and roll.
- Recover to level flight:
  - Apply noseup elevator.
  - Apply stabilizer trim, if necessary.
  - Adjust thrust and drag as necessary.

After recovering the aircraft, flight crews should assess any damage that may have occurred and the present situation. Crews may consider methods to further improve controllability (shifting CG, adjusting flaps or gear or speedbrake, trim, descending, control wheel breakouts, differential thrust, nonnormal procedures, etc.) as the situation dictates. Crews should use the guidance available, consider the issues, and in some cases, validate performance by checks of controllability.